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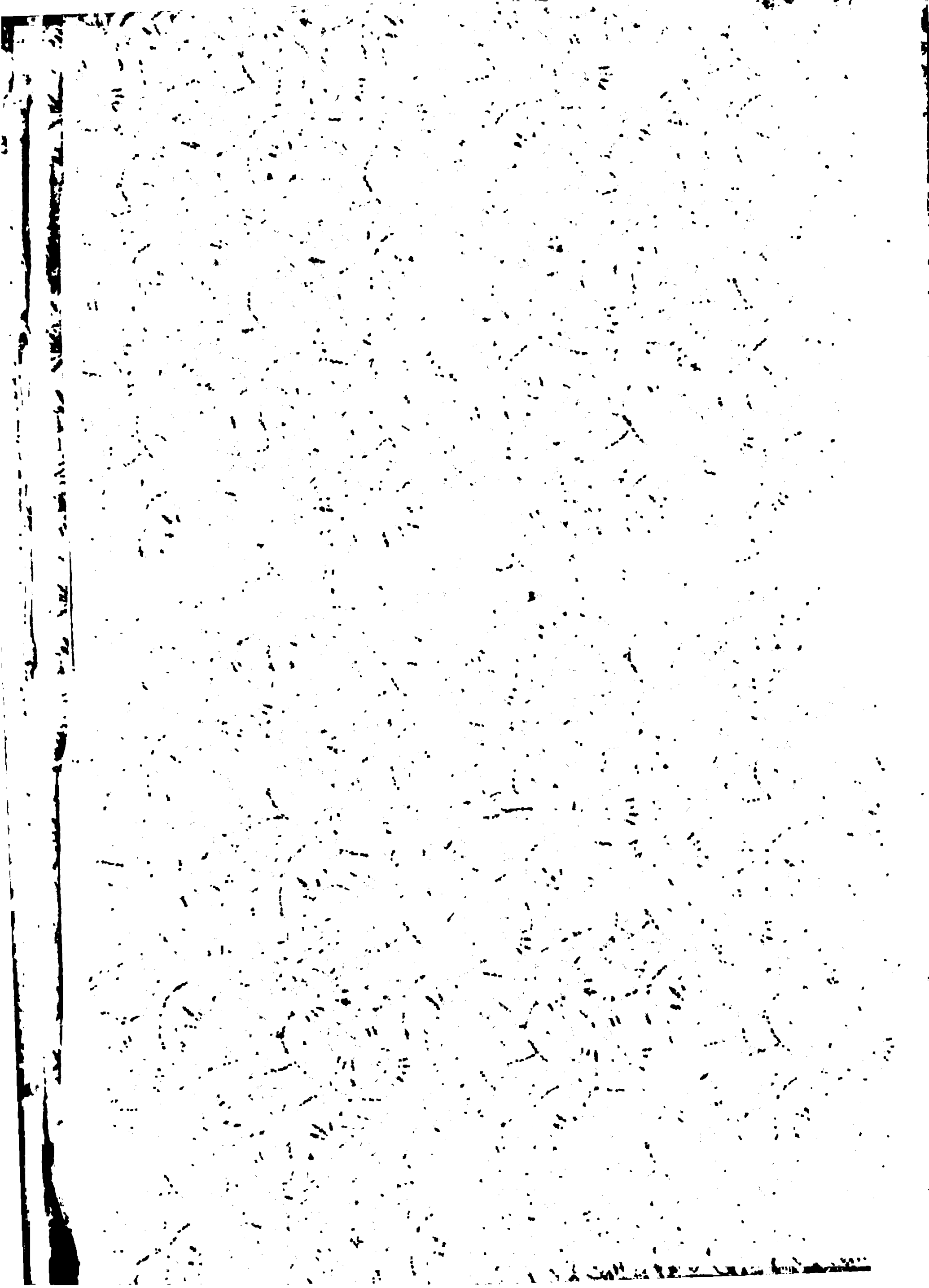

THE CYCLOPÆDIA

OF

ELECTRICAL ENGINEERING

PHOTOGRAVURE, GEBBIE & HUSSON CO. LTD

Samuel F. B. Morse

INVENTOR OF THE ELECTRIC TELEGRAPH

THE CYCLOPÆDIA OF

Electrical Engineering

CONTAINING A

HISTORY OF THE DISCOVERY AND APPLICATION OF ELECTRICITY

WITH ITS PRACTICE AND ACHIEVEMENTS FROM THE
EARLIEST PERIOD TO THE PRESENT TIME

THE WHOLE BEING A

PRACTICAL GUIDE

TO ARTISANS, ENGINEERS AND STUDENTS INTERESTED IN THE
PRACTICE AND DEVELOPMENT OF ELECTRICITY, ELECTRIC
LIGHTING, MOTORS, THERMO-PILES, THE TELEGRAPH,
THE TELEPHONE, MAGNETS AND EVERY OTHER
BRANCH OF ELECTRIC APPLICATION

COMPILED FROM THE MOST RECENT AND BEST WORKS ON THE
SUBJECT BY M. SLINGO, A. BROOKER, DR. ALFRED RITTER
VON URBANITZKY, JOHN PERRY AND OTHERS

WITH NEARLY 600 ILLUSTRATIONS
AND TWO PHOTOGRAVURE PORTRAITS ON STEEL

*

PHILADELPHIA
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1895

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PREFACE.

We wish to say, first of all, that this cyclopædia, like all other cyclopædias, *is a compilation;* but, with the exception of the History of Electricity, it is strictly a compilation of all that is best and newest in *applied electricity*. We know from our large experience with artisans and students in connection with the sale of our Engineers' Encyclopædia of the Steam Engine, that a work which furnishes reliable and practical information worthy of being called a "tool of trade," is always welcome.

We therefore copy from the preface of two of the most important works in this combination, the first being a work just published in London, *Electrical Engineering for Electric Light Artisans and Students, by Wm. Slingo, Principal of the Telegraphist's School of Science, and Director of the Electrical Engineering Section of the People's Palace, London,* and A. Brooker, Instructor in Electrical Engineering at the Telegraphist's School of Science, London.

"We have designed this book to cover the extensive syllabus of the City and Guilds of London Institute, and have so enlarged its scope as to make it embrace the requirements not only of those actually employed in the electric lighting industry, but also of those who, while having little or no electrical knowledge, have under their supervision various kinds of electrical machinery. The work should therefore prove of service to such men as marine, railway and tramway engineers, naval officers, municipal officials, and managers of mines and factories.

"We recognize to the full the fact that, as a rule, the most successful electrical engineers are evolved from good mechanical engineers, and have striven to give our readers, even though they may possess no previous electrical knowledge, a clear insight into the purely scientific as well as the practical part of the subject. Every effort has, however, been made to embrace only the essential branches of the pure science, omitting those which, while interesting and serviceable in other fields, are not required in electric lighting or the electrical transmission of power. It is hoped also that we have succeeded in the difficult task of explaining the subject clearly and in simple language. The close connection between the three kinds of electrical phenomena, static or frictional, dynamic or current, and magnetic, has been carefully explained and made to follow naturally. It is believed that the fact that magnetism is primarily but a consequence of dynamic electricity, or the more or less permanent effect on certain substances of an electrical disturbance, instead of being a separate and distinct series of phenomena, has not hitherto been so plainly and unhesitatingly expressed. It is our firm conviction that in the near future this view of the question is the one which will be universally adopted. The conception of "lines of force" is one of great value to the student, and he will find them here reasoned about as having a tangible existence. It would be impossible to describe every piece of apparatus or machinery in actual use, and we have selected those which, while having proved in practice to be among the best in their respective classes, also serve to illustrate in the readiest manner the laws and principles involved. In a few cases, however, the apparatus can scarcely be said to have been successfully applied, but they have been introduced as indicating the highest present developments in directions in which success will probably be attained.

"Although primary batteries are not used to any great extent in electric lighting, except for testing and other similar operations, yet a considerable amount of space has been devoted to them, and to the experiments which can readily be performed by their aid, because long experience has taught us that they afford in the readiest way a clear insight into the fundamental principles of the science and the various laws so far discovered.

"An unusally large number of the explanations have been based upon Ohm's law and its consequences. Mathematical formulæ and explanations have, where possible, been avoided; where they do occur they are invariably simple, and generally accompanied by arithmetical examples. As they merely supplement the ordinary explanations, they can usually be ignored without the meaning being missed; but those able to solve a simple equation will find very little indeed which cannot easily be followed.

"W. S."
"A. B."

The early part of the work (to page 622) being devoted to Electrical Engineering, of which Messrs. Slingo and Brooker are the authors, the next important divisions—THE TELEGRAPH and THE TELEPHONE—are translations from the great German work by Dr. Alfred Ritter von Urbanitzky, who, in his brief preface to his original work upon which the present treatise is based, thus describes his purpose:—

"In its power to assume always that form of energy which happens to be the most useful, lies the great importance of Electricity. This importance has been brought home to the public at large by means of the many recent exhibitions. Public interest has been roused, and there is everywhere a desire for information, and a demand for a guide through this mysterious and far-extended territory. Although there is no want at present of works and periodicals which treat of the science of electricity, it is not everybody's business to go through fifty volumnes to pick out from amongst the useful and useless that which is needed, and finally to retain just enough to make up one volume.

"The task of saving the general reader that trouble I have undertaken, and have sought to convey a clear insight into the whole science of modern electro-technics, without requiring on the reader's part any special knowledge beyond that of ordinary education. The very complete index is further intended to make the work of use as a book of reference."

To emphasize the principal objects of the work, an Introduction by Professor John Perry reviews the following essential characteristics:—

"1. The method of following up analogies as far as possible. To this we have already referred.

"2. The advisability of keeping in view the older methods and instruments, so as not to allow recent discoveries to cause them to be regarded as useless. Instruments that have been for a time regarded merely as toys, may suddenly be brought into demand for practical purposes, and ought not to be lost sight of. It is becoming the fashion, for instance, to look upon frictional or statical electric machines as things of the past; but there are several discoveries of late years which seem to hint that they may yet be utilized to a greater extent than hitherto. As an example, Professor Lodge has shown that dust and vapor suspended in the air can be 'settled' by an electric discharge, consisting of a continuous series of electric sparks. This fact, when once stated, has speedily been applied to clear the atmosphere in lead-smelting works from the fumes of volatilized lead. Almost contemporaneously with this discovery, comes the invention of the ingenious influence machine of Wimshurst, which produces with a minimum of difficulty and mechanical labor, a continuous series of such sparks, and appears admirably adapted for any purpose—of which more may possibly be discovered—requiring the simple production of electric discharges through the air.

"Our aim has been to supply that information in a form suitable for the general inquirer, and yet to connect with it detailed and definite facts and figures which may be of service to technical students and professional workmen.

"We have only to state in conclusion, that the draft translation of the original work (which has received, however, very free handling) has been executed by Mr. Emil Beyer. And we have also to thank the numerous electrical engineers or inventors who have rendered valuable aid in bringing the work up to date, by supplying information (often accompanied by illustrations) and revising the proof-sheets of the text. Amongst these we are particularly indebted to Messers. Ayrton and Perry, Mr. James Wimshurst, Mr. Alexander Schanschieff, the Brush Company, the Exchange Telegraph Company, and Messrs. Siemens, Edison & Co., Gerard & Co., Higgins, and Fuller."

The remainder of the work—comprising PHOTOPHONE, PHEROPE, PHONOGRAPH, and THERMO-PILES—are all from the latest and best authorities.

There may be an apparent repetition of the subject of "*Electricity as a Motive-Power*," as applied to Street Railways in America ; but it will be found that all that has been said on this and on other branches relating to motive power is absolutely necessary for the completeness of the work.

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HISTORY OF ELECTRICITY.

THE name of the philosopher who first observed that amber when rubbed possesses the property of attracting and repelling light bodies is generally recorded to have been Thales of Miletus, who described this remarkable property (B. C. 600), and both Theophrastus (B. C. 321) and Pliny (A. D. 70) mention the power of amber to attract *straws* and *dry leaves*. The same authors speak of the *lapis lyncurius*, which is supposed to be a mineral called *tourmaline*, as possessing the same property.

The electricity of the torpedo fish was also known to the ancients. Pliny informs us that when touched by a spear it paralyzes the muscles and arrests the feet, however swift; and Aristotle adds that it possesses the power of benumbing men, as well as the fishes which serve for its prey. The influence of electricity on the human body, and the electricity of the human body itself, were also known in ancient times. Anthero, a freedman of Tiberius, was cured of the gout by the shocks of the torpedo; and Wolimer, the king of the Goths, was able to emit sparks from his own body.

Eustathius (A. D. 415), who records this fact, also states that a certain philosopher, while dressing and undressing, emitted occasionally sudden crackling sparks, while at other times flames blazed from him without burning his clothes.

Such are the scanty gleanings of electrical knowledge which we derive from the ancient philosophy; and though several writers of the middle ages have made occasional references to these facts, and even attempted to speculate upon them, yet they added nothing to the science, and left an open field for the researches of modern philosophers.

Dr. Gilbert, of Colchester, England (A. D. 1600), may therefore be considered as the founder of the science of electricity, as he appears to have been the first philosopher who carefully repeated the observations of the ancients, and applied to them the principles of philosophical investigation. In order to determine if other bodies possessed the same property as amber, he balanced a light metallic needle on a pivot, and observed whether or not it was affected by causing the excited or rubbed body to approach to it. In this way he discovered that the following bodies possess the property of attracting light substances: Amber, gugates or jet, diamond, sapphire, carbuncle, rock crystal, opal, amethyst, vincentina or Bristol stone, beryl, crystal, paste for false gems, glass of antimony, flags, belemnites, sulphur, gum-mastic, sealing-wax of lac, hard resin, arsenic, sal gem, mica, and alum.

These various bodies attracted, with different degrees of force, not only straws and light films, but likewise metals, stones, earths, wood, leaves, thick smoke, and all solid and fluid bodies. Among the substances which are not excited by friction, Gilbert enumerated emerald, agate, carnelian, pearls, jasper, chalcedony, alabaster, porphyry, coral, marble, Lydian stone, flints, hæmatites, mugris (*emery* or *corundum*), bones, ivory, hard woods, such as cedar, ebony, juniper, and cypress, metals and natural magnets.

Having thus determined the bodies which were capable, as well as those which were incapable, of electrical excitation, Dr. Gilbert was desirous of ascertaining the circumstances which were most favorable to the production of electricity. When the wind blew from the north and east, and when the air was dry, the body was excited in about ten minutes after the friction commenced; but when the wind was in the south, and the air moist, the attractive power of the body was greatly diminished, and in some cases it could not be excited at all.

The celebrated Mr. Boyle (A. D. 1675) added many new facts to the science of electricity, and he has given a full account of them in his "Experiments on the Origin of Electricity." By means of a suspended needle, he discovered that amber retained its attractive virtue after the friction which excited it had ceased; and though smoothness of surface had been regarded as advantageous for excitation, yet he found a diamond which in its rough state exceeded all the polished ones and all the electrics which he had tried, having been able to move a needle three minutes after he had ceased to rub it. He found also that heat and *tersion* (or the cleaning or wiping of any body) increased its susceptibility of excitation; and that if the attracted body were fixed, and the attracting body movable, their mutual approach would still take place. To Dr. Gilbert's list of electrics Mr. Boyle added the resinous cake which remained after evaporating one-fourth part of good oil of turpentine; the dry mass which remains after distilling a mixture of petroleum and strong spirit of nitre, glass of antimony, glass of lead, caput mortuum of amber, white sapphire, white amethyst, diaphanous ore of lead, carnelian, and a green stone supposed to be a sapphire.

To these discoveries of Mr. Boyle, his illustrious contemporary, Otto Guericke (born 1602, died 1686), added the highly important one of *electric light.* Having cast a globe of sulphur in a glass sphere, the glass was broken, and the sulphur ball mounted upon a revolving axis, and excited by the friction of the hand. By this means he discovered that light and sound accompanied strong electrical excitation, and he compares the light to that which is exhibited by breaking lump sugar in the dark. With this powerful apparatus Guericke verified on a greater scale the results obtained by his predecessors, and obtained several new ones of very considerable importance. He found that a light body, when once attracted by an excited electric, was repelled by it, and was incapable of a second attraction until it had been touched by some other body, and that light bodies suspended within the sphere of influence of an excited electric possessed the same properties as if they had been excited.

To Sir Isaac Newton (born 1642, died 1727) the science of electricity owes some important observations. He seems to have been the first person who constructed an electrical machine of glass. "A globe of glass," says he, "about eight or ten inches in diameter, being put into a frame where it may be swiftly turned round its axis, will in turning shine when it rubs against the palm of one's hand applied to it; and if at the same time a piece of white paper or a white cloth, or the end of one's finger, be held at the distance of about a quarter of an inch or half an inch from that part of the glass when it is most in motion, the electric vapor which is excited by the friction of the glass against the hand will, by dashing against the white paper, cloth, or finger, be put into such an agitation as to emit light, and make the white paper, cloth, or finger appear lurid like a glow-worm, and in rushing out of the glass will sometimes push against the finger so as to be felt. And the same things have been found by rubbing a long and large cylinder of glass and amber with a paper held in one's hand, and continuing the friction till the glass grew warm." * We owe also to Sir Isaac a beautiful experiment on the excitation of electricity on the side of a disc of glass opposite to the side which was rubbed. Having fixed a round disc of glass at the distance of one-third of an inch from one end of a brass hoop or ring, and one-eighth of an inch from another, he placed small pieces of thin paper within the brass ring and upon a table, so that the lower surface of the glass was one-eighth of an inch distant from the table. He then rubbed the upper surface of the glass, and he observed the pieces of paper "leap from one part of the glass to the other, and twirl about in the air." Upon sliding his finger upon the upper side of the glass, he also observed that the pieces of paper, as they hung under the glass, inclined this way or that according as he moved his finger. The Royal Society had ordered this experiment to be tried at their meeting of December 16, 1675; and in order to ensure its success, had obtained the above account of it from Sir Isaac. The experiment, however, failed, and the sec-

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* *Optics*, query 8th.

retary requested the loan of Sir Isaac's apparatus, and inquired whether or not he had secured the papers from being moved by the air which might have somewhere stolen in. In Sir Isaac's reply, dated December 21, he recommended them to rub the glass "with stuff whose threads may rake its surface, and if that will not do, to rub it with the finger-ends to and fro, and knock them as often upon the glass." By means of these directions the society succeeded with the experiment on January 13, 1676, when they used "a scrubbing brush of short hog's bristles, and the heft of a knife made with whalebone." *

Mr. Francis Hawksbee (A. D. 1705), one of the most active and ingenious experimental philosophers of his age, added many new facts to the science. In 1705 he communicated to the Royal Society several curious experiments on what he calls "the mercurial phosphorus." He showed that light could be produced by passing common air through mercury placed in a well-exhausted receiver. The air rushing through the mercury blew it up against the sides of the glass that held it, "appearing all around like a body of fire, consisting of abundance of glowing globules." The phenomenon continued till the receiver was half full of air. When the mercury was made to descend in vacuo from the top to the bottom of a receiver about twenty-one inches high, it fell in minute particles, "like a shower of fire, in a very surprising manner." In repeating this experiment with about three pounds of mercury, and making it break into a shower by dashing it against the crown of another glass vessel, *flashes resembling lightning*, of a very pale color, and very distinguishable from the rest of the produced light, were dashed from the crown of the glass, sometimes horizontally, and at other times upwards and downwards. Mr. Hawksbee likewise showed that considerable light may be produced from mercury, by giving it motion before the receiver was quite exhausted; and that even in the open air "abundance of particles of light are discoverable by shaking quicksilver in a glass."

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* Brewster's *Life of Sir Isaac Newton*, pages 307, 308.

In a subsequent series of experiments on the attraction of bodies in vacuo, he showed that light was generated by the swift attrition of amber on woollen; that a purple light was produced by the attrition of glass on woollen, and that a considerable light was developed by the attrition of glass on glass in vacuo, and in common air, or under water. During the attrition of glass on woollen Hawksbee "observed the light to break from the agitated glass *in as strange a form as lightning*," particularly when he used some list of cloth that had been drenched in spirit of wine. In all these experiments Hawksbee was not aware that the light which he observed was that of electricity.

Like Sir Isaac Newton, Hawksbee used a glass globe capable of revolving in a wooden frame, and by its assistance he made a great number of experiments, which are not sufficiently important to be given in detail. The following experiment, however, is too interesting to be omitted. Having coated more than one-half of the inside of a glass globe with sealing wax, which in some places was an eighth of an inch thick, and therefore absolutely opaque, he exhausted it and put it in motion. When his hand was applied to excite it, the form of his hand was distinctly seen in the concave surface of the wax, as if it had become transparent. The same result was obtained when pitch or common brimstone was substituted in place of sealing-wax.

We have already seen that Hawksbee observed the resemblance between the electric spark and lightning. Dr. Wall (A. D. 1703) went a step farther, and compared the crackling and the flash of excited amber to thunder and lightning. The crackling he found to be fully as loud as that of charcoal on fire when the finger was held at a little distance from the amber after it had been drawn gently and slightly through a piece of woollen cloth.

One of the most ardent experimentalists of this time was Mr. Stephen Gray, a fellow of the Royal Society. In his first paper, which was published in 1720, he showed that electricity could be excited by the friction of feathers, hair, silk, linen, woollen, paper, leather, wood, parchment, and gold-beaters' skin. Several of these bodies exhibited light in the dark, especially after they had been warmed; but all of them attracted light bodies, and sometimes at the distance of eight or ten inches.

The communication of electricity to bodies not capable of excitation was the next discovery of Mr. Gray. An ivory ball, and various other substances of a metallic, animal and vegetable nature, were made to attract light bodies by connecting them with strings, wires, or pieces of wood, with one extremity of an excited glass tube; and by suspending pack-threads of different lengths with silken threads, he was able to transmit the electrical influence in any direction to distances of 50, 147, 293, and finally 765 and 886 feet.

In order to determine if the electric attraction is proportioned to the quantity of matter in bodies, Mr. Gray and Mr. White made two cubes of oak about six inches square, the one solid and the other hollow. When suspended by hair lines, and similarly electrified by an excited glass tube, both the cubes attracted and repelled leaf brass at the same time and to the same height. Hence Mr. Gray concluded *that it was the surface of the cubes only which attracted.*

The conducting powers of fluids and of the human body were next ascertained by Mr. Gray. Having blown a soap bubble with an electrified tobacco pipe, he found that the lower part of the bubble attracted small pieces of Dutch metal; and when a boy eight or nine years old, and weighing forty-seven pounds, was suspended upon hair lines, he found that every part of his body exercised a strong electrical action upon light bodies, and hence he concluded "that animals receive a greater quantity of electrical effluvia." When an excited tube was held above water or quicksilver placed in little ivory dishes, the fluid was attracted upwards into little conical mounds, accompanied with a snapping noise and a discharge of light from their summit. In sunshine small particles of water rose from the top of the fluid cone, and sometimes a fine stream of water like a fountain, from which there arose a fine steam or vapor. Hot water was attracted much more powerfully, and at a much greater distance, and the steam was more distinctly visible. Mercury did not rise so high as the water; but the snapping noise was louder, and continued much longer, than when water was employed.

Mr. Gray now set himself to discover "whether there might not be a way found to make the property of electrical attraction more permanent in bodies." Having procured iron ladles of several sizes, he melted the substances given in the following table. They were then set by in the ladle to cool and harden, and afterwards being replaced on the fire so as to allow what was next the bottom and sides of the ladle to melt, the ladle was inverted, and the substance taken out. These bodies at first would not attract light substances till their temperature was nearly that of a hen's egg; but when cold they attracted ten times farther than at first. In order to preserve these bodies in a state of attraction, he wrapped them up in flannel or white paper or black worsted stockings, and then put them into a large fir box till they were used. The following is Mr. Gray's list of electrics thus formed:

NAMES.	Weight Avoird.		Time when made.
	lbs.	oz.	
Fine black rosin	2	0	Jan. 31.
Stone pitch and black rosin	2	2	Jan. 31.
Fine rosin and bees' wax	2	1	Feb. 1.
Stone pitch	1	7	Feb. 1.
Stone sulphur	3	6	Feb. 4.
Shell-lac	10	0	Feb. 10.
Fine black rosin	10	4	Feb. 10.
Bees' wax and rosin	9	0	Feb. 12.
Rosin 4, gum-lac 1 part	10	0	Feb. 12.
Sulphur	18	0	Feb. 15.
Stone pitch	10	12	Feb. 16.
Black rosin	23	0	Feb. 23.
White rosin	7	12	Feb. 25.
Gum-lac	11	14	Feb. 26.
Gum-lac and black rosin	9	12	Feb. 26.
Gum-lac 4, rosin 1 part	17	8	Feb. 28.
Gum-lac, fine black rosin	28	4	March 2.
Cylinder of blue sulphur	19	4	March 20.
Large cone of ditto	30	0	March 29.
Cake of sulphur	11	4	April 29.

Mr. Gray continued for thirty days to observe every one of these bodies, and at the end of that time he found that they attracted as vigorously as at the first or second day, and some of them continued to preserve their attraction for more than four months.

While Mr. Gray was pursuing his career of discovery in England, M. Dufay, of the Academy of Sciences (A. D. 1733), and superintendent of the Royal Botanic Gardens, was actively employed in the same researches. He found that all bodies, whether solid or fluid, could be electrified by an excited tube, by setting them on a glass stand slightly warmed, or only dried; and that those bodies which are in themselves least electrical received the greatest degree of electricity from the approach of the glass tube. He found that electricity was transmitted more easily along pack-thread when it was wetted, and that it might be supported upon glass tubes in place of silk-lines; and in this way he conveyed it along a string 1,256 feet long.

M. Dufay repeated Mr. Gray's experiments on the human body by suspending a child on silken strings; but having suspended himself in a similar manner, he discovered that an electrical spark, accompanied with a crackling noise, took place when any other person touched him, and he has described the prickling sensation like the burning from a spark of fire, which is at the same time felt either through the clothes or on the skin. He found that the same effects took place in other living animals, but that if the carcass of an animal was suspended, there were no snappings or sparks, but merely a still, uniform light observed in the dark.

The great discovery of M. Dufay, however, was that of two different kinds of electricity, to which he gave the names of *vitreous* and *resinous*, and the importance of which he did not fail to recognize. He has given the name of *vitreous* electricity to that which is produced by exciting *glass*, rock crystal, precious stones, hair of animals, wool, and many other bodies; and the name of *resinous* to that which is produced by exciting resinous bodies, such as amber, copal, gum-lac, silk, paper, thread, and a number of other substances. The characteristic of those two electricities was, that a body with *vitreous electricity* attracted all bodies with *resinous electricity*, and repelled all bodies with *vitreous electricity;* while a body with *resinous electricity* attracted all bodies with *vitreous electricity*, and repelled all bodies with *resinous electricity*. Two electrified silk threads, for example, repel each other, and also two electrified woollen threads; but an electrified silk thread will attract an electrified woollen thread. Hence it is easy to determine whether any body possesses vitreous or resinous electricity. If it *attracts* an electrified silk thread, its electricity will be vitreous; if it *repels* it, it will be resinous. This important discovery seems to have been made about the same time by Mr. White by a series of independent observations.

Mr. Gray repeated and varied the experiments of M. Dufay, and made many new ones, which our limited space will not permit us to detail. Like Hawksbee and Dr. Wall, he recognized the similarity between the phenomena of electricity and those of thunder and lightning; and he expresses a hope "that there may be found out a way to collect a greater quantity of electric fire, and consequently to increase the force of that power, which, by several of these experiments, *si licet magnis componere parva*, seems to be *of the same nature with thunder and lightning.*"

The discoveries which we have now recounted began to rouse the activity of the German and Dutch philosophers. To the electrical machine used by Newton and Hawksbee Professor Boze, of Wittemberg, added the *prime* conductor, which at first consisted of an iron or tin tube supported by a man standing upon cakes of resin; but it was afterwards suspended by silken strings. Professor Winkler, of Leipsic, substituted the *cushion* in place of the hand for exciting the revolving globe; and Professor Gordon, of Erfurt, a Scotch Benedictine monk, first used a glass cylinder, eight inches long and four broad, which he caused to revolve by means of a bow and string. By these means electrical sparks of great size and intensity were produced, and by their aid various combustible substances, both fluid and solid, were inflamed. In 1744 M. Ludolph, of Berlin, succeeded in firing, by the electrical spark, the ethereal spirit of Frobenius. Winkler did the same by a spark from his finger; and he succeeded in inflaming French brandy and other weaker spirits after they had been heated. Mr. Gordon kindled spirits by a jet of electrified water. Dr. Miles inflamed phosphorus by the electric spark; and oil, pitch and sealing-wax, when strongly heated, were set on fire by similar means.

These striking effects were all produced by the electricity obtained immediately from an excited electric; but a great step was now made in the science by the discovery of a method of accumulating and preserving the electric fluid in large quantities. The author of this great invention is not distinctly known; but there is reason to believe that a monk of the name of Kleist, a person of the name of Cuneus, and Professor Muschenbroeck, of Leyden, had each the merit of an independent inventor. The invention by which this accumulation was effected was called the *Leyden Jar* or *Phial*, because it was principally in that city where it was either invented or tried. Having observed that excited electrics soon lost their electricity in the open air, and that their loss was accelerated when the atmosphere was charged with moisture or other conducting materials, Muschenbroeck conceived that the electricity of bodies might be retained by surrounding them with bodies which did not conduct it. In putting this idea to the test of experiment, they electrified some water in a glass bottle, and a communication having been made between the water and the prime conductor, while the bottle was held by an assistant, who was trying to disengage the communicating wire, he received a sudden shock in his arms and breast, and thus established the efficacy of the Leyden jar (1745).

Sir William Watson made some important experiments at this period of our history. He succeeded in firing gunpowder by the electric spark; and by mixing the gunpowder with a little camphor he discharged a musket by the same power. He also fired inflammable air by the electric spark; and he kindled both spirits of wine and inflammable air by means of a drop of cold water, and even with ice. In the German experiments the fluid or solid to be inflamed was set on fire by an electrified body; but Sir William Watson placed the fluid in the hands of an electrified person, and set it on fire by causing a person not electrified to touch it with his finger.

Sir William Watson first observed the flash of light which attends the discharge of the Leyden phial, and it is to him that we owe the present improved form of the Leyden phial, in which it is coated both without and within with tinfoil. Dr. Bevis indeed had suggested the outside coating, and, at Mr. Smeaton's recommendation, he coated a pane of glass on both sides, and within an inch of the edge with tinfoil; but still the idea of coating the jar undoubtedly belongs to Sir William Watson.

A party of the Royal Society, with the President at their head, and Sir William Watson as their chief operator, entered upon a series of magnificent experiments, for the purpose of determining the velocity of the electric fluid, and the distance to which it could be conveyed. The French savans had conveyed the influence of the Leyden jar through a circuit of 12,000 feet; and in one case the basin at the Tuileries, containing about an acre of water, formed part of the circuit; but the English philosophers made a more complete series of experiments, of which the following were the results:

1. That in all their operations, when the wires have been properly conducted, the electrical commotions from the charged phial have been very considerable only when the observers at the extremities of the wire have touched some substance readily conducting electricity with some part of their bodies.

2. That the electrical commotion is always felt most sensibly in those parts of the bodies of the observers which are between the conducting wires and the nearest and the most non-electric substance; or, in other words, so much of their bodies as comes within the electrical circuit.

3. That on these considerations we infer that the electrical

power is conducted between these observers by any non-electric substances which happen to be situated between them and contribute to form the electrical circuit.

4. That the electrical commotion has been perceptible to two or more observers at considerable distances from each other, even as far as two miles.

5. That when the observers have been shocked at the end of two miles of wire, we infer that the electrical circuit is four miles, viz.: two miles of wire, and the space of two miles of the non-electric matter between the observers, whether it be water, earth, or both.

6. That the electrical commotion is equally strong, whether it is conducted by water or dry ground.

7. That if the wires between the electrifying machine and the observers are conducted on dry sticks, or other substances non-electric in a slight degree only, the effects of the electrical power are much greater than when the wires in their progress touch the ground, or moist vegetables, or other substances in a great degree non-electric.

8. That by comparing the respective velocities of electricity and sound, that of electricity, in any of the distances yet experienced, is nearly instantaneous.

In the following year these experiments were resumed with the view of ascertaining the absolute velocity of electricity at a certain distance, and it was found "that through the whole length of a wire 12,276 feet the velocity of electricity was instantaneous."

One of the most important discoveries of the present period was that of Sir William Watson, who proved "that the glass tubes and globes had not the electrical power in themselves, but only served as the first movers or determiners of that power." In rubbing a glass tube while standing upon a cake of wax he was surprised to observe that no spark could be obtained from his body by any other person touching any part of him. But if a person not electrified held his hand near the tube while it was rubbing, the snapping was very sensible. The great discovery of *plus* and *minus* electricity which was afterwards made by Franklin was distinctly announced by Sir William Watson. He lays it down as a law, that in electrical operations there is an afflux of electric fluid to the globe and the conductor, and also an efflux of the same matter from them. In the case of two insulated persons, the one in contact with the rubber and the other with the conductor, he observed that either of them would communicate *a much stronger spark to the other than to any bystander. The electricity of the one,* he says, *became more rare than it is naturally, and that of the other more dense,* so that the density of the electricity in the two insulated persons differed more than that between either of them and a bystander.

Our limits will not permit us to give a detailed account of the various ingenious experiments which were about this time made by Le Monnier, Nollet, Winckler, Ellicott, Jallabert, Boze, Menon, Smeaton and Miles. In 1746 Le Monnier confirmed the result previously obtained by Mr. Gray, that electricity is communicated to homogeneous bodies in proportion to their surfaces only. M. Boze discovered that capillary tubes which discharged water by drops afforded a continued stream when electrified. The Abbé Nollet ascertained that electricity increases the natural evaporation of fluids, and that the evaporation is hastened by placing them in non-electric vessels. M. Jallabert confirmed the result previously obtained by Watson, that electricity passes through the substance of a conducting wire, and not along its surface. Smeaton found that the red-hot part of an iron bar could be as strongly electrified as the cold parts on each side of it. Dr. Miles kindled common lamp spirits by a stick of black sealing-wax excited by dry flannel. Mr. Ellicott conceived that the particles of the electric fluid repel each other, while they attract those of all other bodies. Mr. Mowbray discovered that the vegetation of two myrtles was hastened by electrifying them; a result which Nollet confirmed in the case of vegetating seeds. The Abbé Menon found that cats, pigeons, sparrows and chaffinches lost weight by being electrified for five or six hours, and that the same result was true of the human body; and hence it was concluded that electricity augments the insensible perspiration of animals.

Passing over the scientific fables of John Pivati, of Venice, we arrive at the auspicious period when Dr. Franklin raised electricity to the dignity of a science, 1747, and connected it with that tremendous agency which had so often terrified the moral and convulsed the physical world. The thunderbolt had frequently descended from heaven upon its victims; but mortal genius had now learned to bring it down in chains, to disarm its fury, and to convert it into an useful and even friendly element.

One of the first labors of the American philosopher was to present, in a more distinct form, the theory of plus and minus electricity, which Sir W. Watson had been the first to suggest. He showed that electricity is not created by friction, but merely collected from its state of diffusion through other matter by which it is attracted. He asserted that the glass globe, when rubbed, attracted the electrical fire, and took it from the rubber, the same globe being disposed, when the friction ceases, to give out its electricity to any body which has less. In the case of the charged Leyden jar, the inner coating of tinfoil had received more than its ordinary quantity of electricity, and was therefore electrified *positively* or *plus*, while the outer coating of tinfoil having had its ordinary quantity of electricity diminished, was electrified *negatively* or *minus*. Hence the cause of the shock and spark when the jar is discharged, or when the superabundant plus electricity of the inside is transferred by a conducting body to the defective or minus electricity of the outside. This theory of the Leyden phial Franklin established in the clearest manner, by showing that the outside and the inside coating possessed opposite electricities, and that, in charging it, exactly as much electricity is added on one side as is subtracted from the other. The copious discharge of electricity by points was observed by Franklin in his earliest experiments, and also the power of points to conduct it copiously from an electrified body. Hence he was furnished with a simple method of collecting electricity from other bodies; and he was thus enabled to perform those remarkable experiments which we shall now proceed to explain.

Hawksbee, Wall and Nollet had successively suggested the similarity between lightning and the electric spark, and between the artificial snap and the natural thunder. Previous to the year 1750 Dr. Franklin drew up a statement, in which he showed that all the general phenomena and effects which were produced by electricity had their counterpart in lightning. Like the electric spark, lightning moves in a crooked and irregular direction. Lightning strikes the highest and most pointed bodies, and electricity does the same. They both inflame combustibles, fuse metals, destroy animal life, produce blindness in animals, render common sewing needles magnetic, and reverse the polarity of needles that have been magnetized. Notwithstanding these points of resemblance, direct experiment was still necessary to establish his views. He waited anxiously for the erection of a spire at Philadelphia, by means of which he might bring down the electricity of a thunder-storm; but his patience being exhausted, he conceived the idea of sending up a kite among the clouds themselves. With this view he made a small cross of two light strips of cedar, the arms being sufficiently long to reach to the four corners of a large thin silk handkerchief when extended. The corners of the handkerchief were tied to the extremities of the cross, and when the body of the kite was thus formed, a tail, loop, and string were added to it. The body was made of silk to enable it to bear the violence and wet of a thunder-storm. A very sharp pointed wire was fixed at the top of the upright stick of the cross, so as to rise a foot or more above the wood. A silk riband was tied to the end of the twine next the hand, and a key suspended at the junction of the twine and silk. In company with his son, Franklin raised the kite like a common one, in the first thunder-storm, which happened in the month of June, 1752. To keep the silk riband dry, he stood within a door, taking care that the twine did not touch the frame of the door; and when the thunder-clouds came over the kite he watched the state of the string. A cloud passed without any electrical indications, and he began to despair of success. He saw, however, the loose filaments of the twine standing out every way, and he found them to be attracted by the approach of his finger. The suspended key gave a spark on the application of his knuckle, and when the string had become wet with the rain, the electricity became abundant; a Leyden jar was charged at the key, and by the electric fire thus obtained spirits were inflamed, and all the other electrical experiments performed which had been formerly made by excited electrics. In subsequent trials with another apparatus, he found that the clouds were sometimes positively and sometimes negatively electrified, and thus demonstrated the perfect identity of lightning and electricity.

Having thus succeeeded in drawing the electric fire from the clouds, Franklin immediately conceived the idea of protecting buildings from lightning by erecting on their highest parts pointed iron wires or conductors communicating with the ground. The electricity of a hovering or a passing cloud would thus be carried off slowly and silently; and if the cloud was highly charged, the electric fire would strike in preference the elevated conductors.

The attention of European philosophers was now directed to the great discovery of Franklin, and various individuals fearlessly sought to repeat his experiments. Among these Professor Richman of St. Petersburg was one of the most enterprising. He had undertaken a series of experiments on the electricity of the atmosphere, and for this purpose he had erected an electrical gnomon, which consisted mainly of a Leyden jar, communicating with an iron rod, which rose four or five feet above the roof of his house, and an electrometer formed of a linen thread with half a grain of lead, the angular ascent of which on the face of a divided quadrant indicated the force of the accumulated electricity. On the 9th of August, 1752, Professor Richman obtained from the end of the rod electrical flashes which could be heard at several feet of distance; and if any person touched the apparatus, a sharp stroke was felt in the hand and arm. On the 31st of May, 1753, the electric fire exploded from the apparatus with such a force that it was heard at the distance of three rooms from the apparatus. On the 6th of August, 1753, the professor had prepared and adjusted his apparatus, and having heard the sound of distant thunder, he left a meeting of the Academy of Sciences and took with him his engineer, Mr. Sokolow, to draw any interesting phenomena that might occur. On their arrival at the professor's house, the plummet of the electrometer was elevated four degrees from the perpendicular; and while the philosopher was describing to his friend the dangerous consequences that might take place if the thread should rise to 45°, a tremendous burst of thunder terrified the imperial city. Richman leant his head over the gnomon to observe the indications of the electrometer, and in this stooping position, with his head a foot from the iron rod, a huge globe of bluish-white fire, about the size of Mr. Sokolow's fist, shot from the iron rod to the professor's head, with a report like that of a pistol. The blow was fatal; he fell back upon a chest and instantly expired. Sokolow was stupefied and benumbed by a sort of steam or vapor, and the red-hot fragments of a metallic wire struck his clothes and covered them with burnt marks. As soon as he recovered from his surprise Sokolow ran out of the house, acquainting every person with the accident which had taken place. In the meantime Madam Richman, alarmed by the thunder-stroke, hastened to the chamber, and found her husband apparently lifeless, in the attitude of sitting upon the chest, and leaning against the wall. Medical aid was instantly obtained, but though a vein was opened, from which no blood would flow, and though every attempt was made to restore life by violent friction and other means, they were all fruitless. A small quantity of blood dropped from the mouth when the body was turned, and on the forehead there was a red spot, from the pores of which a few drops of blood oozed out. Several red and blue spots, like leather shrunk by burning, were found on the left side, the back and other parts of the body. The shoe upon the professor's left foot was burst open, and a blue mark appeared on the foot beneath the aperture. There was no corresponding hole in the stocking, and the coat was uninjured. When the body was opened, twenty-four hours after death, there was no appearance of injury either in the brain or the cranium: a little extravasated blood appeared in the cavities below the lungs, and in the lungs towards the back, which were of a dark brown color. The heart, glands and smaller intestines were all inflamed; but the entrails were uninjured. About seventy rubles of silver which were in the left coat pocket were not altered by the electric fluid. Immediately after the accident the house was filled with a sulphureous vapor. A clock which stood in the corner of the adjoining room was stopped; the ashes from the hearth were scattered about the room; the door-case of the room was rent asunder, and a piece of the door itself actually torn off. The Leyden jar was also broken, and the metallic filings which it contained thrown about the room.

One of the most active and ingenious laborers in the field of electrical science was the ingenious Mr. John Canton (1753). Before his time it had been assumed as indisputable that the same kind of electricity was invariably produced by the friction of the same electric; that glass, for example, yielded always *vitreous*, and amber always *resinous* electricity. Having roughened a glass tube by grinding its surface with emery and sheet lead, he found that it possessed vitreous or positive electricity when excited with oiled silk, but *resinous electricity when excited with new flannel.* He found, in short, that vitreous or resinous electricity may be developed at will in the same tube, by altering the surfaces of the tube and the exciting rubber, and according as the one or the other is most affected by their mutual friction. This he illustrated by the very beautiful experiment of removing the polish from one-half of the tube. In this case the different electricities were excited with the same rubber at a single stroke, and, what is very curious, *the rubber was found to move much easier over the rough than over the polished half.*

Mr. Canton likewise discovered that glass, amber, sealing-wax and calcareous spar were all electrified positively when taken out of mercury; and hence he was led to the important practical discovery, that an amalgam of mercury and tin was most efficacious in exciting glass when applied to the surface of the rubber. Mr. Canton found also that any body placed within the electric atmosphere of another body acquired the electricity opposite to that of the body in whose atmosphere it was placed, and that the whole air of a room could be electrified either positively or negatively, and made to retain it for a considerable time.

Signor Beccaria (1753), a celebrated Italian, kept up the spirit of electrical discovery in Italy; and in his work on natural and artificial electricity he has given us the results of many important original investigations. He showed that water is a very imperfect conductor of electricity, that its conducting power is proportional to its quantity, and that a small quantity of water opposes a powerful resistance to the electric fluid. He succeeded in making the electric spark visible in water, by discharging shocks through wires that nearly met in tubes filled with water. In this experiment the tubes, though sometimes eight or ten lines thick, were burst in pieces. Beccaria likewise demonstrated that air adjacent to an electrified body gradually acquired the same electricity; that the electricity of the body is diminished by that of the air; and that the air parts with its electricity very slowly. He considered that there was a mutual repulsion between the particles of the electric fluid and those of air, and that in the passage of the former through the latter a temporary vacuum was formed.

The science of electricity owes several practical as well as theoretical observations to Mr. Robert Symmer (1759). In pulling off his stockings in the evening Mr. Symmer had often remarked that they not only gave a crackling noise, but even emitted sparks in the dark. The electricity was most powerful when a silk and a worsted stocking had been worn on the same leg, and it was best exhibited by putting the hand between the leg and the stockings, and pulling them off together. The one stocking being then drawn out of the other, they appeared more or less inflated, and exhibited the attractions and repulsions of electrified bodies. Mr. Symmer's first trials were accidentally made with *black* silk stockings, but he was surprised to find that *white* ones produced no electricity. Two white silk stockings, or two black ones, when put on the same leg and taken off, gave no electrical indications. When a black and a white stocking were put on the same leg, and at the end of ten minutes taken off, they were so much inflated when pulled asunder, *that each of them showed the entire shape of the leg, and at the distance of a foot and a half they rushed to meet each other.* With worsted stockings, also, nothing but the combination of black and white produced electricity. As it was troublesome to electrify the stockings by putting them on and taking them off the leg, Mr. Symmer excited the stockings by drawing them on the hand, which, however, produced a weaker degree of electricity. The electricity was in this case more permanent, and the effects were more powerful when the stockings were new or newly washed. When an excited white and black stocking are presented to each other, they attract one another, inclining to each other at the distance of three feet, and at a less distance rushing together with surprising violence, becoming as flat as so many folds of silk when they are joined. "But what appears most extraordinary is, that when they are separated, and removed at a sufficient distance from each other, their electricity does not appear to have been in the least impaired by the shock they had in meeting. They are again inflated, again attract and repel, and are as ready to rush together as before. When this experiment is performed with two black stockings in one hand and two white in the other, it exhibits a very curious spectacle; the repulsion of those of the same color, and the attraction of those of different colors, throws them into an agitation that is not unentertaining, and makes them catch each at that of its opposite color, at a greater distance than one would expect. When allowed to come together they all unite in one mass. When separated they resume their former appearance, and admit of the repetition of the experiment as often as you please, till their electricity, gradually wasting, stands in need of being recruited."

In the course of these experiments Mr. Symmer accidentally threw a stocking out of his hands, and some time afterwards he found it sticking to the paper-hangings of the room. They stuck also to the painted panelling, and often continued for a whole hour suspended upon the hangings.

Mr. Symmer's attention was next directed to the force of cohesion between stockings of black and white silk, and he found that from ten ounces to nine pounds weight was necessary to separate the stockings, according to their weight, or according as the rough or smooth surfaces were in contact.

Mr. Symmer likewise found that a Leyden jar could be charged by the stockings either positively or negatively, according as the wire from the neck of the jar was presented to the black or white stockings. When the electricity of the white stocking was thrown into the jar, and on that the electricity of the black one, or *vice versa*, the jar will not be electrified at all. With the electricity of two stockings he charged the jar to such a degree that the shock from it reached both his elbows; and by means of the electricity of four silk stockings he kindled spirits of wine in a teaspoon which he held in his hand, and the shock was at the same time felt from the elbows to the breast. Independent of these curious experiments, Mr. Symmer had the merit of having first maintained the theory of two distinct fluids, not independent of each other, as Dufay supposed them to be, but co-existent, and, by counteracting each other, producing all the phenomena of electricity. He conceived that when a body is said to be *positively electrified*, it is not simply that it is possessed of a larger share of electric matter than in a natural state; nor, when it is said to be *negatively electrified*, of a less; but that, in the former case, it is possessed of a larger portion of one of these active powers, and in the latter, of a larger portion of the other; while a body, in its natural state, remains unelectrified, from an equal balance of these two powers within it.

Contemporary with Symmer were Delaval, Wilson, Cigna, Kinnersley, and Wilcke. M. Delaval found that the sides of vessels that were perfect conductors were non-conductors, and that animal and vegetable bodies lost their conducting power when reduced to ashes. Mr. Wilson discovered that when two electrics are rubbed together, the harder of the two is generally electrified positively and the other negatively, but always with opposite electricities. Cigna made many curious experiments by using silk ribands in place of the silk stockings of Symmer. Kinnersley, the friend of Franklin, made some important experiments on the elongation and fusion of iron wires, when a strong charge was passed through them in a state of tension; and Wilcke brought to light many new phenomena respecting the spontaneous electricity produced by the melting of electric substances.

The pyro-electricity of minerals, or the faculty possessed by some minerals of becoming electric by heat, and of exhibiting negative and positive poles, now began to attract the notice of philosophers. There is reason to believe that the *lyncurium* of the ancients, which, according to Theophrastus, attracted light bodies, was the *tourmaline*, a Ceylon mineral, in which the Dutch had early recognized the same attractive property, whence it got the name of *Aschentrikker*, or attracter of ashes. In 1717 M. Lemery exhibited to the Academy of Sciences a stone from Ceylon which attracted light bodies; and Linnæus, in mentioning the experiments of Lemery, gives the stone the name of *Lapis Electricus*. The Duke de Noya had heard at Naples that Count Pichetti had seen at Constantinople a stone called *tourmaline*, which attracted and repelled light bodies; and in 1758 he purchased some of them in Holland, and, assisted by MM. Daubenton and Adanson, he made a series of experiments with them, which were published separately.

This curious subject, however, had engaged the attention of M. Æpinus, a celebrated German philosopher, who published an account of them in 1756. Hitherto nothing had been said respecting the necessity of heat to excite the tourmaline; but it was shown by Æpinus that a temperature between 99½° and 212° of Fahrenheit was requisite for the development of its attractive powers. Mr. Benjamin Wilson, Priestley, and Canton continued the investigation; but it was reserved for the Abbé Haüy to throw much light on this curious branch of the science. He found that the electricity of the tourmaline decreased rapidly from the summits or poles towards the middle of the crystal, where it was imperceptible; and he discovered that if a tourmaline is broken into any number of fragments, when excited, each fragment has two opposite poles. Haüy discovered the same property in the Siberian and Brazilian topaz, borate of magnesia, mesotype, prehnite, sphene, and calamine. He also found that the polarity which minerals receive from heat has a relation to the secondary forms of their crystals, the tourmaline, for example, having its resinous pole at the summit of the crystal which has three faces, and its vitreous pole at the summit which has six faces. In the other pyro-electrical crystals above-mentioned, Haüy has detected the same deviation from the rules of symmetry in their secondary crystals which occurs in tourmaline. Mr. Brard discovered that pyro-electricity was a property of the axinite; and more recently Sir David Brewster detected it, as we shall afterwards see, in a variety of other minerals.

In repeating and extending the experiments of Haüy, Sir David Brewster discovered that various artificial salts were pyro-electrical; and he mentions the tartrate of potash and soda, and the tartaric acid, as exhibiting this property in a very strong degree. He likewise made many experiments with the tourmaline when cut into thin slices, and reduced to the finest powder, in which state each atom preserved its pyro-electricity; and he has shown that *scolezite* and *mesolite*, even when deprived of their water of crystallization, and reduced to powder, preserve their property of becoming electrical by heat. When this white powder is heated and stirred about by any substance whatever, it collects in masses like new-fallen snow, and adheres to the body with which it is stirred.

In addition to his experiments on the tourmaline, Æpinus made several on the electricity of melted sulphur; and, in conjunction with Wilcke, he investigated the subject of electric atmospheres, and discovered a beautiful method of charging a plate of air by suspending large wooden boards coated with tin, and having their surfaces near each other, and parallel. Æpinus, however, has been principally distinguished by his ingenious theory of electricity, which he has explained and illustrated in a separate work which appeared at St. Petersburg in 1759. This theory is founded on the following principles: 1. The particles of the electric fluid repel each other with a force decreasing as the distance increases. 2. The particles of the electric fluid attract the particles of all bodies, and are attracted by them, with a force obeying the same law. 3. The electric fluid exists in the pores of bodies; and while it moves without any obstruction in non-electrics, such as metals, water, etc., it moves with extreme difficulty in electrics, such as glass, rosin, etc. 4. Electrical phenomena are produced, either by the transference of the fluid from a body containing more to another containing less of it, or from its attraction and repulsion when no transference takes place.

The electricity of fishes, like that of minerals, now began to excite very general attention. The ancients, as we have seen, were acquainted with the benumbing power of the torpedo, but it was not till 1676 that modern naturalists attended to this remarkable property. The Arabians had long before given this fish the name of *raad* or lightning; but Redi was the first who communicated the fact that the shock was conveyed to the fisherman by means of the line and rod which connected him with the fish. Lorenzini published engravings of its electrical organs; Reaumur described the electrical properties of the fish; Kæmpfer compared the effects which it produced to lightning; but Bancroft was the first person who distinctly suspected that the effects of the torpedo were electrical. In 1773 Mr. Walsh and Dr. Ingenhouz proved, by many curious experiments, that the shock of the torpedo was an electrical one; and Dr. Hunter examined and described the anatomical structure of its electrical organs. Humboldt, Gay Lussac, and M. Geoffroy pursued the subject with success; and Mr. Cavendish constructed an artificial torpedo, by which he was able to produce artificially the actions of the living animal. The subject was more recently investigated by Dr. Todd, Sir Humphry Davy, and Dr. John Davy.

The power of giving electric shocks has been discovered also in the *Gymnotus Electricus*, the *Silurus Electricus*, the *Trichiurus Indicus*, and the *Tetraodon Electricus*. The most interesting and the best known of these singular fishes is the *Gymnotus* or Surinam eel. Its electrical organs have been minutely described by Hunter and Geoffroy; Dr. Williamson, Dr. Gordon, and Mr. Walsh have also published interesting details of its peculiar electrical powers; and Humboldt has given the most romantic account of the combats which are carried on in South America between the gymnoti and the wild horses in the vicinity of Calabozo.

Among the cultivators of electricity the late Mr. Cavendish is entitled to a distinguished place. Before he had any knowledge of the theory of Æpinus, he had composed and communicated to the Royal Society a theory of electrical phenomena nearly the same as that of the German philosopher. As Mr. Cavendish, however, had carried the theory much farther, and considered it under a more accurate point of view, he did not hesitate to give his paper to the world.

Mr. Cavendish made some accurate experiments on the relative conducting power of different substances. He found that the electric fluid experiences as much resistance in passing through a column of water one inch long, as it does in passing through an iron wire of the same diameter 400,000,000 inches long, and hence he concludes that rain or distilled water conducts 400,000,000 times more than iron wire. He found that the water, or a solution of one part of salt in one of water, conducts a hundred times better than fresh water; and that a saturated solution of sea-salt conducts seven hundred and twenty times better than fresh water. Mr. Cavendish likewise determined by nice experiments that the quantity of electricity in coated glass of a certain area increased with the thinness of the glass; and that in different coated plates the quantity was as the area of the coated surface directly, and as the thickness of the glass inversely.

Although electricity had been employed as a chemical agent in the oxidation and fusion of metals, yet it is to Mr. Cavendish that we owe the first of those brilliant inquiries which have done so much for the advancement of modern chemistry. By means of the electric spark he succeeded in decomposing atmospheric air. By using different proportions of oxygen and hydrogen, and examining the product which they formed after explosion with the electric spark, he obtained a proportion when the product was pure water. He was equally successful in the more difficult experiment of exploding oxygen and nitrogen; but when he combined seven measures of oxygen with three measures of nitrogen, he obtained from their explosion *nitric acid.* As several foreigners had failed in repeating this interesting experiment, Mr. Cavendish, aided by Mr. Gilpin, exhibited it publicly before the leading members of the Royal Society on the 6th of December, 1787.

The decomposition of water by the electric spark was first effected by MM. Paets, Troostwyk, and Deiman; and improved methods of doing it were discovered and used by Dr. Pearson, Mr. Cuthbertson, and Dr. Wollaston.

As a chemical agent, however, electricity was now destined to transfer its supremacy to another science. The great discovery made by Galvani in 1790, that the contact of metals produced muscular contraction in frogs, and the invention of the Voltaic pile, in 1800, by M. Volta, of Como, led to the establishment of a new science called *Galvanism* or *Voltaic Electricity*, which, though now proved to be identical with common electricity, requires to be treated in a separate article. The chemical effects of the Voltaic pile far transcended those of ordinary electricity, and enabled Sir Humphry Davy to decompose the earths and the alkalies, and thus to create a new epoch in the history of chemistry.

Contemporary with Mr. Cavendish was M. Coulomb, one of the most eminent experimental philosophers of the last century. Anxious to determine the law of electrical action, he invented for this purpose an instrument called a *torsion balance*, which has since his time been universally used in all delicate researches, and which is particularly applicable to the measurement of electrical and magnetical actions. Æpinus and Cavendish had considered the action of the electrical fluid as diminishing with the distance; but M. Coulomb proved, by a series of elaborate experiments, that it varied like gravity in the inverse ratio of the square of the distance. Dr. Robison, of Glasgow, had previously determined, without, however, having published his experiments, that in the mutual repulsion of two similarly electrified spheres the law was slightly in excess of the inverse duplicate ratio of the distance, while in the attraction of oppositely electrified spheres the deviation from that ratio was in defect; and hence he justly concluded that the law of electrical action was similar to that of gravity.

Adopting the hypothesis of two fluids, Coulomb investigated experimentally and theoretically the distribution of electricity on the surface of bodies. He determined the law of its distribution between two conducting bodies in contact; he measured the density of the electricity in different points of two globes in contact; he ascertained the distribution of electricity among several globes (whether equal or unequal) placed in contact in a straight line; he measured the distribution of electricity on the surface of a cylinder, and its distribution between a globe and cylinder of different lengths but of the same diameter. His experiments on the dissipation of electricity possess also a high value. He found that the momentary dissipation was proportional to the degree of electricity at the time, and that when the electricity was moderate its dissipation was not altered in bodies of different kinds or shapes. The temperature and pressure of the atmosphere did not produce any sensible change; but the dissipation was nearly proportional to the cube of the quantity of moisture in the air. In examining the dissipation which takes place along imperfectly insulating substances he found that a thread of gum-lac was the most perfect of all insulators; that it insulated ten times better than a dry silk thread, and that a silk thread covered with fine sealing-wax insulated as powerfully as gum-lac when it had four times its length. He found also that the dissipation of electricity along insulators was chiefly owing to adhering moisture, but in some measure also to a slight conducting power.

Towards the end of the last century a series of experiments was made by MM. Laplace, Lavoisier and Volta, from which it appeared that electricity is developed when solid or fluid bodies pass into the gaseous state. The bodies which were to be evaporated or dissolved were placed upon an insulating stand, and made to communicate by a chain or wire with a Cavallo's electrometer, or with Volta's condenser, when it was suspected that the electricity increased gradually. When sulphuric acid diluted with three parts of water was poured upon iron filings, inflammable air was disengaged with a brisk effervescence, and at the end of a few minutes the condenser was so highly charged as to yield a strong spark of negative electricity. Similar results were obtained when charcoal was burnt on a chafing dish, or when fixed air or nitrous gas was generated from powdered chalk by means of the sulphuric and nitrous acids.

M. Volta, who happened to be at Paris when these experiments were made, and who took an active part in them, had subsequently observed that the electricity produced by evaporation was always negative. He found that burning charcoal gives out negative electricity; and in other kinds of combustion he obtained distinct electrical indications.

In this state of the subject M. Saussure undertook a series of elaborate experiments on the electricity of evaporation and combustion. In his first trials he found that the electricity was sometimes positive and sometimes negative when water was evaporated from a heated crucible of iron; but he afterwards found it to be always positive both in an iron and a copper crucible. In a silver and in a porcelain crucible the electricity was negative. The evaporation of alcohol and of ether in a silver crucible also gave *negative* electricity. M. Saussure made many fruitless trials to obtain electricity from combustion, and he likewise failed in his attempts to procure it from evaporation without ebullition.

Many valuable additions were about this time made to electrical apparatus, as well as to the science itself, by Van Marum, Cavallo, Nicholson, Cuthbertson, Brooke, Bennet, Read, Morgan and Henley; but our limits will not permit us to do anything more than thus notice their labors.

The application of analysis to electrical phenomena may be dated from the commencement of the present century. Coulomb had considered only the distribution of electricity on the surface of spheres; but Laplace undertook to investigate its distribution on the surface of ellipsoids of revolution, and he showed that the thickness of the coating of fluid at the pole was to its thickness at the equator as the equatorial is to the polar diameter, or, what is the same thing, that the repulsive force of the fluid, or its tension at the pole, is to that at the equator as the polar is to the equatorial axis.

M. Biot has extended this investigation to all spheroids differing little from a sphere, whatever may be the irregularity of their figure. He likewise determined analytically that the losses of electricity form a geometrical progression when the two surfaces of a jar or plate of coated glass are discharged by successive contacts; and he found that the same law regulates the discharge when a series of jars are placed in communication with each other.

It is to M. Poisson, however, that we are mainly indebted for having brought the phenomena of electricity under the dominion of analysis and placed it on the same level as the more exact sciences. By assuming the hypothesis of two fluids, he has deduced theorems for determining the distribution of the electric fluid on the surface of two conducting spheres when they are either placed in contact or at any given distance; and the truth of these theorems has been established by experiments performed by Coulomb long before the theorems themselves had been investigated.

The cultivation of the new science of Voltaic electricity had now withdrawn the attention of experimental philosophers from that of ordinary electricity. The splendor of its phenomena. as well as its association with chemical discoverv, contributed to give it popularity and importance; but the discoveries of Galvani and Volta were destined, in their turn, to pass into the shade, and the intellectual enterprise of the natural philosophers of Europe was directed to new branches of electrical and magnetical science. Guided by theoretical anticipations, Professor H. C. Oersted, of Copenhagen, in 1820, laid the foundations of the science of *Electro-magnetism.* He found that the electrical current of a galvanic trough, when made to pass through a platinum wire; acted upon a compass needle placed below the wire; and upon repeating the experiment, he discovered the fundamental law, that *the magnetical effect of the Voltaic current had a circular motion round the current*, or round the *conductor*, or the wire through which the current passed. M. Ampère, of Paris, soon afterwards made the important discovery that two wires conducting electrical currents, when suspended so as to be capable of motion, *attracted* each other when the currents moved in the *same direction*, and *repelled* each other when they moved in *opposite* directions; or, to express the fact more simply, *two points of electrical currents repel each other by their similar sides, and attract each other by their opposite sides;* so that, as Professor Oersted remarks, *an electric current contains a revolving action, exhibiting every appearance of polarity.*

In 1820, M. Arago, Sir H. Davy, and Dr. Seebeck of Berlin, without being acquainted with each other's labors, discovered the power of the electric current to impart magnetism to iron and steel needles; but the most singular discovery on this branch of the subject was made by M. Savary, who found that small steel needles, placed at different but very short distances from a wire conducting an electrical current, are magnetized in different directions. Needles in contact with the wire are magnetized in the usual or *positive* direction; while needles at the distance of 1.1 millimeter, or $\frac{1}{24}$ of an inch, are magnetized in an opposite direction, which he calls *negative.* At the distance of two inches from the wire there was a neutral line in which the needles were not magnetized at all. When the distance of the unmagnetized needle was increased from three to eight millimeters it again became positively magnetic, the maximum effect taking effect at the distance of 5½ millimeters. Between the distance of 8.6 and 21.4 millimeters the magnetism was a second time negative, the effect increasing from 8.6 to 14.6, and again reaching the vertical or zero point at 21.4. Beyond the distance of twenty-three millimeters the magnetism was again positive. With different conducting wires M. Savary found, that within certain limits the maximum intensity is produced at a greater distance from the wire, and the number of alterations of positive and negative direction is also greater in proportion, as the wire is shorter in proportion to the length of the helix. When needles are placed parallel to the axis of a helix of narrow windings, they all receive the same kind of magnetism; but when the electrical charge is increased from one jar to a battery of twenty-two superficial feet, six alternations, viz., three positive and three negative, are obtained. When Voltaic electricity is substituted for ordinary electricity, the alternations are destroyed by a continued current, but appear when the current is established only for an instant.

These curious experiments were followed by those of Professor Erman, of Berlin, who found that when an electrical discharge passes through the centre of a circular disc of steel, and in a line perpendicular to its surface, no apparent magnetism is developed; but when a slit is made in the plate, or a sector cut out of it, the side of the disc opposite to the slit, or the sectoral opening, exhibits the opposite magnetism. MM. Gay Lussac and Welther obtained the same result with a steel ring.

The discovery of *thermo-electricity* by Dr. Seebeck, in 1822, gave a new impulse to this branch of science. In studying the influence of heat in Galvanic arangements, he was led to believe that magnetism might be developed in two metals forming a circuit when the equilibrium of heat in them was disturbed. He accordingly joined a semicircular piece of bismuth with a similar piece of copper, so as to form a circle by their union; and when one of the junctions was heated an electrical current was produced, which could show its existence only by the magnetic needle, and which exhibited all the magnetical properties of an electrical current.

In the same year in which Dr. Seebeck made this remarkable discovery, the rotation of a magnetical needle round an electrical current, and of a body transmitting an electrical current round a magnet, were exhibited in a series of beautiful and highly ingenious experiments by Dr. Faraday, whose subsequent discoveries place him at the head of the cultivators of this most interesting science.

These experiments were followed by those of Arago, Barlow, Seebeck, Herschel, and Babbage, in which a revolving plate of copper gives a rotary motion to a magnetic needle conveniently suspended; but notwithstanding the ingenuity and talent with which this subject was treated by these eminent individuals, it is to Dr. Faraday that we owe a complete analysis and explanation of this curious phenomenon.

This explanation was founded on the great discovery of the evolution of electricity from magnetism, by which Dr. Faraday laid the foundation of the new science of magneto-electricity. By means of a series of simple and beautiful experiments with the celebrated magnets of Dr. Gowin Knight, and with the powerful magnet of Professor Daniel, Dr. Faraday obtained the most unequivocal and striking electrical effects, though the intensity of the electricity was very feeble, and its quantity small. He obtained a distinct though feeble spark; he succeeded in convulsing the limbs of a frog by means of a magnet; and he perceived also the sensation on the tongue and the flash before the eyes, but he could not effect chemical decomposition by magnetism. Besides obtaining these important results, Dr. Faraday has clearly established the laws according to which a magnet develops magnetic currents. He applies these laws to the explanation of the reciprocal action of revolving magnets and metals, and he adduces unquestionable proofs of the production of electricity by terrestrial magnetism.

These important results have been more recently extended by Dr. Faraday and others. M. Pixii observed attractions and repulsions in the electricity evolved by magneto-electric induction; and by an ingenious and powerful apparatus he obtained a great degree of divergence in the gold leaves of an electrometer. At the meeting of the British Association at Oxford, in June, 1832, Dr. Faraday, by means of Mr. Snow Harris's electrometer, subsequently described, succeeded in heating a wire by magneto-electric induction. By means of the magneto-electric apparatus of M. Pixii already referred to, he and M. Hachette decomposed water, and obtained the oxygen and hydrogen in separate tubes.

In the progress of his electrical researches, Dr. Faraday found it necessary for their further prosecution to establish either the identity or the distinction of the electricities excited by different means; and in a paper of great value he has established beyond a doubt the identity of common electricity, Voltaic electricity, magneto-electricity, thermo-electricity, and animal electricity. The phenomena exhibited in these five kinds of electricity do not differ in kind, but merely in degree; *and in this respect they vary in proportion to the variable circumstances of quantity and intensity, which can at pleasure be made to change in almost any one of the kinds of electricity, as much as it does between one kind and another.*

Dr. Faraday was anxious to determine the relation by measure of ordinary and voltaic electricity; and after various excellent experiments, he obtained an approximation, and judging from magnetical force only, "that two wires, one of platinum and one of zinc, each one-eighteenth of an inch in diameter, placed five-sixteenths of an inch apart, and immersed to the depth of five-eighteenths of an inch in acid consisting of one drop of oil of vitriol, and four ounces distilled water at a temperature of about 60°, and connected at the other extremities by a copper wire eighteen feet long and one-eighteenth of an inch thick (being the wire of the galvanometer coils), yield as much electricity in eight beats of a watch, or in $\frac{8}{150}$ths of a minute (or 3.2 seconds), as the electrical battery (of fifteen jars) charged by thirty turns of the large machine in excellent order. The same result was found to be true in the case of chemical force."

In the course of his investigations relative to electro-chemical composition, Dr. Faraday was led to observe the effects due to a very general law of electric conduction which had not formerly been recognized. He found that solid bodies assume the power of conducting electricity during liquefaction, and lose this conducting power during congelation. The voltaic electricity produced by a battery of fifteen troughs, or a hundred and fifty pairs of four-inch plates powerfully charged, was incapable of passing through a thin film of ice three-sixteenths of an inch thick; but when the ice was melted, the electricity passed in such quantities as to deflect the magetic needle 70°. This insulation, however, exhibited by ice is not effective with electricity of exalted intensity. In making this experiment with other solid bodies, Dr. Faraday chose those which, being solid, at common temperatures, were fusible, and of such a composition as, for other reasons connected with electro-chemical action, led to the conclusion that they would be able to replace water. When the electric current passed through the solid body employed, there was no chemical decomposition; but when the body was liquefied or fused, the decomposition took place. The bodies which Dr. Faraday found to be subject to this law will be found in our section on Electrical Conduction. The degree of conducting power conferred upon bodies by liquidity is generally very great. In water it is the feeblest of all; and in the various oxides, chlorides, salts, etc., it is given in a much higher degree, some a hundred time greater, than in the case of pure water.

In studying the phenomena of induction, Dr. Faraday was led to a beautiful theory of inductive action, which threw a new light upon every department of electricity. While Cavendish, Poisson, and other distinguished cultivators of the science considered induction as a force excited at a distance, and in straight lines, he was led to regard it as an *action of contiguous particles*, or particles near each other, consisting of a species of polarity in the particles of the *dielectric* or insulating medium, through or across which the electric forces are acting. When an electrified body induces electricity in a conductor, it does it by *polarizing* all the intermediate particles of the dielectric, that is by exciting the opposite electricities in the particles near it, and by these particles producing the same effect from particle to particle, till it is transferred to the conductor. The particles which are thus polarized are not supposed to be material atoms of the dielectric, but merely points or centres of force pervading all space and penetrating all material bodies. When such contiguous particles communicate their forces slowly to one another, *insulation* or *coercion*, as it has been called, is produced; and when rapidly, conduction is the result. This polarization of dielectrics was placed beyond a doubt by the experiments of Faraday and Matteucci in the case of solids and fluids, if not for air and the gases. By means of this fine theory, which was confirmed by experiments, M. Mosotti succeeded in explaining the law of electrical forces discovered by Coulomb.

In an able memoir published at Turin in 1845, M. Plana gave the results of his researches on the distribution of the electric fluid on the surface of conductors. Without taking into consideration the cause of the retention of electricity on the surface of conductors, he treated the problem of its distribution in three cases—in the case where the spheres are in contact, in the case where they are separated by any interval, and in the case where the separation is very small compared with the distance of their centres. He gave also a more rigorous demonstration of certain principles, on the relations which exist between the thickness of the electric wire and the forces which emanate from it. From the simple fact, that free electricity distributes itself on the surface of conductors, he demonstrated that the repulsive force in the case of simple physical points is inversely as the square of the distance.

The distribution of electricity on spherical conductors has been successfully pursued by English mathematicians. The celebrated scientist, Mr. Cavendish, had, so early as 1773, made great progress in the inquiry. He demonstrated the remarkable proposition, that unless the electrical force was in the inverse proportion of the square of the distance, the electricity would be distributed through the interior of a charged conductor; and consequently that this law must be true, as the electricity is confined to an infinitely thin film on its surface. We owe also to Cavendish an approximation to the true theory of the Leyden jar, and a determination of the effects produced by connecting conductors with fixed wires.

It was by Mr. Green, a self-taughtmathematician, that the first great advances were made in the mathematical theory of electricity.* "His researches," as Professor William Thomson has observed, "have led to the elementary proposition which must constitute the legitimate foundation of every perfect mathematical structure that is to be made from the materials furnished in the experimental laws of Coulomb. Not only do they afford a natural and complete explanation of the beautiful quantitative experiments which have been so interesting at all times to practical electricians, but they suggest to the mathematician the simplest and most powerful methods of dealing with problems which, if attacked by the mere force of analysis, must have remained forever unsolved." One of the simplest applications of these theorems was to perfect the theory of the Leyden jar, a result which (if we except the peculiar action of the insulating solid medium since discovered by Dr. Faraday) we owe to his genius. He has also shown how an infinite number of forms of conductors may be invented, so that the distribution of electricity in equilibrium on each may be expressible in finite algebraical terms—an immense stride in the science, when we consider that the distribution of electricity on a single spherical conductor, an uninfluenced ellipsoidal conductor, and two spheres mutually influencing one another, were the only cases solved by Poisson; and, indeed, the only cases conceived to be solvable by good mathematical writers.

The work of Mr. Green, which contained these fine researches, though published in 1828, had escaped the notice not only of foreign, but even of British mathematicians; and it is a singular fact in the history of science, that all his general theorems were rediscovered by Professor William Thomson of Glasgow, MM. Charles and Sturm of Paris, and M. Gauss of Göttingen. Professor Thomson, however, pushed his researches much further than his fellow-laborers. He pointed out in 1845 the consistency of Dr. Faraday's experiments with the new theory; and, guided by an analogy between the uniform motion of heat and the distribution of electricity on conductors, or the attractive and repulsive forces excited by electrified bodies, he showed how the peculiar electric polarization discovered by Dr. Faraday in dielectrics, or solid insulators subjected to electric force, is to be taken into account in the theory of the Leyden phial, so as to supply the deficiency in Green's investigations.*

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* *Essay on the Application of Mathematical Analysis to the Theories of Electricity and Magnetism*, Nottingham, 1828.

From the elementary propositions of Mr. Green, Mr. Thomson was led to the beautiful principle of what he calls *electrical images*, which is a new and admirable method of treating a great variety of problems in reference to the distribution of electricity on spherical conductors. "The effect," says Mr. Thomson, "of a body electrified in any given manner upon an uninsulated sphere, is shown to be completely represented by what may be called *the image* of the *electrified body in the sphere;* and a simple geometrical construction is given by which this image may be described. When an electrified body is placed in the neighborhood of two uninsulated spheres, an inductive effect is produced which may be represented by an infinite series of *successive images* in each sphere. An algebraic expression of this result leads to solutions, by means of converging series, of the various problems which occur with reference to the distribution of the induced electricity, and the attractions exerted by the two spheres. Or, when a single conductor, bounded by segments of two spherical surfaces cutting at an angle which is a submultiple of two right angles, is electrified by the influence of a charged body, the effect may be represented by a finite number of images disposed in a symmetrical manner in the circumference of a circle passing through the exciting body, and cutting the two spherical surfaces at right angles. The principle of electrical images in these two cases may be illustrated by a reference to the successive images of a candle placed between two parallel plane mirrors, and to the symmetrically arranged images which are seen in the kaleidoscope." *

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* See *Cambridge and Dublin Mathematical Journal*, Nov., 1845; and *Phil. Mag.*, July, 1854, pp. 42–62.

One of the most remarkable discoveries in electricity which has been made is that of the hydro-electric machine, which we owe to Mr. Armstrong, of Newcastle. On the 29th of September, 1840, William Paterson, who attended a steam-engine at Cramlington Colliery, eight miles from Newcastle, happening to take hold with one hand of the lever of the safety valve of the boiler, while his other hand was in the steam which was issuing from a fissure, received an electric shock. The same effect was produced if he touched any part of the boiler, or any iron work connected with it. The engine-man also found that when one hand was immersed in the jet of steam he gave a shock to every person he touched with the other, whether the person was in contact with the boiler or merely stood on the brickwork which supports it, though the shock was greater when the person touched the boiler. Having heard of these remarkable facts, Mr. Armstrong went to Cramlington Colliery and observed the phenomena, and having constructed a steam apparatus, he found that the place where the electricity was produced was that at which the steam was subjected to friction, and that when the boiler was of wrought-iron the electricity was always *positive*, excepting when he made the steam pass to the discharging aperture through a considerable surface of polished brass. In this case the electricity became very feeble; but when the inside of the brass tube was moistened with dilute nitric acid, the steam from the iron boiler became for the first time *negatively* electrified. By an insulated brass discharging-rod, consisting of a metallic plate at one end and a brass ball at the other, he obtained from 60 to 70 powerful sparks in a minute, the plate being plunged in the issuing steam, and the ball brought into contact with the boiler. Mr. Armstrong was thus led to construct a hydro-electric machine, which gave sparks 22 inches long, and so large, dense, and rapid that they frequently resembled a continuous flame. This machine, with a boiler 6½ feet long by 3½ feet wide, was constructed for the Polytechnic Institution, London, where it long excited the admiration of the public.

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* *Reports of the British Association*, 1847, Trans. Sect., pp. 6, 7.

Mr. Armstrong at the very commencement of his inquiry communicated his discovery to Dr. Faraday, who, with his usual ability, investigated the theory of the machine. He found that the electricity was produced by the friction of the particles of water upon the discharging tube, and that it was not the electricity caused by evaporation. When tubes of glass, metal or wood were used, the electricity of the steam was always negative, and that of the boiler positive, but when a quill tube or a tube of ivory was employed, "the boiler received scarcely any charge, and the stream of steam was also in a neutral state," showing that the electricity was not produced by evaporation. Dr. Faraday also found that the electricity of the issuing current was *negative*, and that of the boiler *positive*, when oil or oil of turpentine was carried forward by the current of steam. When acetic acid was used in the steam globe, the electricity was neutralized.

Properly speaking, the early history of electricity comes to a close here, and the science of electricity commences with the results of the researches of Davy and Faraday. The one who, as it were, prepared the ground was Humphry Davy (born 1778). His researches regarding the influence of the electrical current on chemical compounds were begun in 1806, and led him to the decomposition of the alkaline earths and the discovery of the alkaline metals. Chlorine was found to be an element, and the products of decomposed bodies to be analogous to positive and negative electricity, etc., etc. This observation led to the electro-chemical theory. Although water was decomposed by Carlisle and Nicholson in 1800, no proper explanation of the result could be furnished. Davy, however, proved water to consist of oxygen and hydrogen only.

We owe to Faraday, his pupil, the further working out of Davy's notions. Michael Faraday was without doubt one of the greatest physicists that ever lived. We need not go into the details of his discoveries in many other branches of science. For us, his name is chiefly associated with the law of electro-statics, diamagnetism, and induction. The enormous importance of this discovery of induction may easily be seen by pointing to the present condition of electro-technics, *i. e.*, to the telegraph, telephone, and dynamo machine.

Faraday substituted the term electrode for pole, naming the positive electrode the annode, the negative electrode the kathode. He also constructed the voltameter, by means of which he discovered the laws of electrolysis in 1853.

The discoveries of Siemens, Brush, Edison, Gramme, Thomson, Bell, and others, were rendered comparatively easy by the prior discoveries of Professor Michael Faraday.

John Perry, of London, the celebrated electrician, thus sums up the history of the progress of Electrical Engineering during the last twenty years:

In 1870 Dr. Everett wedded notions of potential to the detached experimental information of a French treatise on electricity, which he translated; and the books of Fleeming Jenkin and Clerk Maxwell, published soon afterwards, completely removed all impediments in the way of electrical students. The full meaning of Ohm's law became clear; electro-motive force, difference of potential, resistance, current, capacity, lines of force, magnetization, chemical affinity, were measurable, and could be reasoned about, and calculations could be made about them with as much certainty as calculations in dynamics. Information was now published which had long been known to the practical electrical engineer, but which had been really unknown to the writers of text-books and the teachers of science. It may be said that from 1870 the teaching of electricity has ceased to be a mere lecture-room exhibition of tricks and startling electrical effects, and has become a more and more widely known science. But it is only since about that time; and while it is useless to speculate on what might have occurred had Sir William Thompson condescended to write in 1857 a text-book on electricity such as he was then capable of producing, it may safely be said that it is very seldom that a man's inability to comprehend how ignorant his contemporaries are has produced such evil effects in retarding the progress of industrial invention.

There can be no doubt that the people of one hundred years hence will wonder that we shall have remained so oblivious of phenomena occurring around us, to which they will not be able to shut their eyes. Of all the many wonderful but simple inventions which they will make themselves, and which are unknown to us, the discovery of a single one at the present time would be a great event. They will probably speak to one another at a distance without any artificial connection between. They will probably be able to see one another's actions at great distances, just as if they were close together.

However, it is not only by the study of the few, but also by the intelligent observation of the many, that discoveries are brought about. We must give to every unit of the population a chance of becoming a Watt or a Faraday. It is by the spread of education among the masses of the people that we are hastening the discovery of new civilizing agents. The history of electrical engineering during the last twenty years is one of the best illustrations that can be given of the fact, that for many people to have some knowledge, however low in level it may be, is as necessary to the development of discovery as for a few people to have knowledge, however high in level. Very slow and difficult has the progress been since the beginning of this century, when the electric arc was discovered; since Faraday's discovery of electro-magnetic induction, which is the principle of all dynamo-electric machines; since Grover invented his gas battery, Ritter his secondary piles, and Planté the germ of the modern accumulator. But between 1860 and 1870, mainly in consequence of the work done by the Science and Art Department, a working knowledge of the principles of the science, which until then had only been known to a few people, became the property of thousands of mechanics, and it may almost be said that the rate of progress in electrical discovery became proportional to the number of people who had some electrical knowledge. The small magneto-electric machine, regarded as a toy for giving shocks, led to the machine invented by Wilde, in 1866, in which excited electro-magnets were employed. In that year Varley and others made independently one of the grandest discoveries of the century, and presently a machine was in use which excited its own field magnets, the type of all dynamo-machines since that time. With this principle of Varley, and using the form of armature employed by Pacinotti in 1860, Gramme invented, in 1871, his famous continuous current generator, which has revealed to the world how much electrical power is obtainable from a small machine.

The world has seldom seen such a period of scientific unrest as occurred from 1878 to 1889; but amidst the multitudes of discoveries and inventions which are the products of that restless period, there are few which were made by the mathematical leaders. Most of them may be regarded as the results of the demand which the workmen had already begun to make for a clear knowledge of the principles which underlie their operations. There were thousands of workmen who were continually asking for advice, or for more knowledge of what was already known to the few; and the few aroused themselves, and put their knowledge in simpler and more exact forms before the world; still discoveries and inventions were made not by the learned few, but by the fortunate few of the unlearned many. We had the Gramme and Siemens dynamo-machines, followed rapidly by a hundred others, so much alike in principle, that when one is clearly understood the principle of another is known after a very short examination. What was wanted for the proper working of an arc electric light became known to the many; and in a short time hundreds of interesting methods of regulating the electric light were abroad. That a filament of carbon in a state of incandescence from the passage of an electric current could be used as a lamp had been known to the few for many years; but immediately after this fact became generally known hundreds of incandescent lamps were invented.

It is to be observed that in attempting to put electric principles before the general reader, the fact that these principles are essentially of a mathematical character cannot be ignored. It is true that in applications of electricity, as in applications of mechanics, the student is often able to arrange apparatus with which many curious phenomena may be observed, without his having much knowledge of electrical or mechanical magnitudes; but there can be no doubt that there is an immense waste of time and knowledge due to attempts of this kind. Without a quantitative knowledge of scientific principles, we have students seeking for the elixir of life, the philosopher's stone, and perpetual motion. The old alchemists certainly made discoveries, and the search for perpetual motion has led to great advancements in science, or, if to nothing else, to the knowledge that there cannot be perpetual motion. It is also quite true that if Mr. Graham Bell had been well acquainted with Fourier's mathematical analysis, he would have scorned to make the experiments which led to the discovery of the telephone. We are, however, too much in the habit of forgetting how numerous are the experimenters of this order who discover nothing whatever, and whose time is completely wasted; and it may be laid down as a general rule for electrical students, that he who has not a quantitative knowledge of the principles of electrical science will only waste his time in making original experiments.

To get exact ideas in any department of physics we have one firm foundation to build upon, namely, that a certain amount of energy, or power of doing work, remains always the same, however it may change its form. We have many sources of electricity: the rubbed plate-glass machine, the induction machine, the voltaic cell, the thermo-pile, the magneto-electric machine, the dynamo-electric machine, and others. To all these some form of energy is given, and they convert this energy, badly or well, into electric energy. To the first two and the last two of those mentioned, mechanical energy is given by hand or from a steam-engine, and this mechanical energy is converted partly into heat, which may be regarded as a loss, and partly into the electric energy which we require; but the electric energy is less in amount than the mechanical energy given to the machine. In a voltaic cell zinc is burned; that is, what may be called chemical energy is used up, and electrical energy is given out. In the thermo-pile again, heat energy is given to the pile, part of it being given out as electrical energy.

Joule's experiments tell us that any generator gives out exactly as much energy as is given to it, but much appears in the form of heat, so that it is the object of an inventor to construct a generator of electrical energy which shall give out as much as possible of the energy supplied to it in the form of electrical energy. A clear distinction must be made between *electricity* and *electrical energy*. A miller does not merely speak of the quantity of water in his mill-dam; he has also to consider the height through which it can fall. A weight of one thousand pounds, falling through a distance of one foot, represents the same energy, that is, can give out the same amount of work in falling, as one pound through one thousand feet. A mere statement, then, of the quantity of electricity given out by a machine is insufficient; it is also necessary to state what is the height or difference of potential through which it is falling. The quantity of electricity in a thunder-cloud is comparatively small, but the difference of potential through which this quantity passes when discharge occurs, is exceedingly great. So it is with the two factors of the electrical energy developed by a glass-plate machine. The quantity of electricity obtainable from the machine per second is comparatively small, but it is like a small quantity of water at an exceedingly great height; whereas, in the other machines mentioned, we have, in the analogy of the miller, a very great quantity of water and a very small difference of level.

The water analogy is very useful, because everybody has fairly exact notions about water, and because, within certain limits, the analogy is a true one. The following table gives it more fully.

Water.	*Electricity.*
1. Steam-pump burns coal and lifts water to a high level.	1. Generator burns zinc, or uses mechanical power, and lifts electricity to a higher level or potential.
2. Energy available is, amount of water lifted × difference of level.	2. Energy available is, amount of electricity × difference of potential.
3. If we let all the water flow away through a channel to a lower level without doing work, its energy is all converted into heat because of frictional resistance of the pipe or channel.	3. If we let all the electricity flow through a wire from one screw of our generator to the other without doing work, all the electrical energy is converted into heat because of resistance of the wire.
4. If we let water work a hoist as well as flow through channels, less water flows than before, less power is wasted in friction.	4. If we let our electricity work a machine as well as flow through wires, less flows than before, less power is wasted through the resistance of the wire.
5. However long and narrow may be the channels, water may be brought from any distance, however great, to give out almost all its original energy to a hoist. This requires a great head and small quantity of water.	5. However long and thin the wires may be, electricity may be brought from any distance. however great, to give out almost all its original energy to a machine. This requires a great difference of potentials and a small current.
6. If a pump produces a very slow continuous flow of water in an endless pipe which may or may not work water-pressure engines by its motion, the work done on every pound of water passing through the pump is called the total available *head*, or pressure, and it is greater than the greatest difference of pressure observable between any two points in the circuit.	6. If a generator produces a flow of electricity in a circuit which may or may not work electro-motors, the energy given to every unit quantity (or coulomb) of electricity passing through the generator is called the electro-motive force of the generator, and it is greater than the greatest difference of potential observable between any two points in the circuit.

In fact, if we could leave out of account the kinetic energy, or energy of motion of water, there is the most exact agreement between the laws of pumps, circuits of pipes, and water-pressure engines, and the laws of electric generators, electric circuits, and electro-motors. It will be readily understood that for some purposes it is necessary to have our electrical energy in the shape of a small quantity of electricity falling through a great difference of potential, and that for other purposes we must have a great quantity of electricity falling through a small difference of potential.

When we possess an electric circuit from a generator, we are able to convert the electric energy into other forms of energy at any place. In every part of the circuit some heat is being produced, and to produce a high temperature at any place it is only necessary to introduce a thin wire, say a platinum wire or carbon filament. Introducing an electro-motor at any place enables us to convert the electric energy into mechanical energy. Thus an electric generator receiving mechanical energy from a steam-engine gives out electric energy; this energy can be conveyed many miles along metallic wires to an electro-motor, which converts it into mechanical energy again.

We have now instruments which enable us to measure the electric power of the distant generator, the power wasted by conversion into heat in the circuit, the electric power received by the motor or lamp, or other useful converter, and the mechanical power or light or heat given out by the motor or lamp; and by easy reasoning we find out what are the conditions for the most efficient transmission of power.

During the last ten years the progress made in electric engineering has been mainly due to improvements in the mechanical arrangements of dynamo machines, electro-motors, arc and incandescent lamps, and in the electric supply cables used in general systems of electric lighting and transmission of power. These improvements have been effected almost altogether by mechanical engineers, whose knowledge of electrical science, ten years ago, was insignificant. There can, therefore, be no doubt that in the hands of the numerous body of practical men who have a pecuniary interest in making such improvements, electrical engineering will rapidly become more important to the community than any other department of civil engineering.

JOHN PERRY.

MR. JOHN PERRY'S TABLE OF ELECTRICAL MAGNITUDES.

(*Some rather approximate.*)

Resistance of

One yard of copper wire, one-eighth of an inch diameter	0.002	ohms.
One mile of ordinary iron telegraph wire	10 to 20	"
Some of our selenium cells	40 to 1,000,000	"
A good telegraph insulator	4,000,000,000,000	"

Electro-motive force of

A pair of copper-iron junctions at a difference of temperature of 1° Fahr.	0.000,01	volts.
Contact of zinc and copper	0.75	"
One Daniell's cell	1.1	"
Mr. Latimer Clark's standard cell	1.45	"
Difference of potential at the terminals of an incandescent lamp used in ordinary lighting	50 to 110	"
Board of Trade limit of difference of potential between any two points in an electric circuit used in continuous current lighting	200	"
Electro-motive force of one of Dr. De la Rue's batteries	11,000	"
Lightning-flashes	probably many millions of volts.	

Currents usually measured—

Using electrometer	almost infinitely small currents.	
Using delicate galvanometer	0.000,000,000,040	amperes.
Current received from Atlantic cable, when 25 words per minute are being sent	0.000,001	amperes.
Current in ordinary land telegraph lines	0.003	"
Current through an ordinary incandescent lamp	0.5 to 1	"
Current from dynamo machine used in electric lighting	5 to 500	"

In any circuit containing a generator of electricity, the electro-motive force of the generator is equal to the current in amperes multiplied by the resistance of the circuit in ohms.

The resistance (in ohms) of any piece of wire forming part of an electric circuit, is equal to the difference of potential (in volts) between its ends divided by the current (in amperes) passing through it.

Rate of production of heat or other forms of energy in watts (746 watts = 1 horse-power): In the whole of a circuit, is a current (in amperes) multiplied by the electro-motive force (in volts). In any wire forming part of a circuit, is the current (in amperes) multiplied by the difference of potential (in volts) between the ends of the wire, or the square of the current (in amperes) multiplied by the resistance (in ohms).

In a 20-candle incandescent light we find that 75 watts are usually expended.

Rate at which electric energy is given to an electro-motor, is the difference of potential at the terminals of the motor (in volts) multiplied by the current (in amperes). This energy is converted partly into heat and partly into mechanical energy by the motor.

Rate at which electric energy is being given out by a generator, is the difference of potential at its terminals (in volts) multiplied by the current (in amperes).

MAGNETISM.

Although magnetism and electricity are treated in dictionaries and cyclopædias under different headings, it will be observed by any one who has read the preceding history of the discovery and application of electricity that the development of our knowledge of magnetism is so interwoven with that of electricity—that the history of one is really the history of the other, and were we to write in detail the history of magnetism, the same names precisely would occur as appear in the preceding pages, with the exception of that part relating to the mariner's compass. Since it has gradually come to the knowledge of scientists that the earth itself is a huge, irregular magnet, charged by the solar rays, it is now generally believed that magnetism is primarily but a consequence of a dynamic electricity, or the more or less permanent effect on certain substances of an electrical disturbance, instead of being a separate and distinct series of phenomena. We, however, for the satisfaction of our readers, give a very brief description of magnetism.

Six centuries before the Christian era it was known to the Greeks that a certain mineral, commonly called lodestone, possesses two very remarkable properties. In the first place, it has the power of attracting iron, and in a lesser degree some other substances—more especially the two metals, nickel and cobalt—with a force which is greater beyond all comparison than the attraction of gravitation, which is always exerted between two portions of matter. In the second place, when a portion of it is suspended, so that it can turn freely in any direction; for example, if it is hung up by a thread passing through its centre of gravity, it always assumes a certain definite direction at a given place on the earth's surface. These properties may be communicated to pieces of iron or steel by simply rubbing them in a certain definite manner with a piece of lodestone. In the case of very soft iron, however, the properties so communicated are very soon lost again.

Any substance which has these properties is called a magnet, and the action of communicating this property to iron is called magnetizing it. The lodestone is a chemical compound of the the metal iron with the gas oxygen, and on account of its possessing the two properties mentioned it is also known as magnetic iron ore, or magnetic oxide of iron.

Humboldt, in the "Cosmos," tells us that three centuries before the Christian era the Chinese caravans were guided on their journeys across the trackless wastes of Tartary by means of a little human figure revolving upon a pivot, and holding in its outstretched hand a fragment of lodestone, so placed that its arm always pointed to the south.

Large magnets are not now manufactured by rubbing iron with lodestone, because, as explained in the body of this book, the electric current provides a means of magnetizing iron and steel very much more powerfully than would be possible merely by aid of the lodestone. The process of magnetizing by rubbing is however still frequently employed as a convenient method of making small magnets, as a piece of steel or iron may be magnetized by rubbing it with any other magnet, whether this be a lodestone or an artificial magnet. By the aid of a moderately strong magnet and a few steel sewing needles, it is easy to make a series of experiments on the principal properties of magnets.

There are several ways in which a needle may be rubbed with a magnet in order to magnetize it, the simplest of these being to stroke the needle always in the same direction from end to end with the same end of a steel magnet made in the shape of a straight or bent bar. If two needles are magnetized in this way and hung up by threads, so that they can move freely, or if they are fixed in small slips of cork, and allowed to float on the surface of water, it will be found that the needles will turn, so that two definite ends are juxtaposed, after which they will approach each other until they come into contact. If both the needles are reversed, so that the opposite ends of each are brought together, they will again attract each other; but if one of the needles is reversed the needles will be found to repel each other.

Repeat this experiment, magnetizing the two needles by stroking them from the eye to the point with one end of the magnet which has been marked. Then hang the needles up, and it will be found that the two points, if brought together, will repel each other, and the two eyes, if brought together, will also repel each other; but a point and an eye will attract each other. It is clear, therefore, that there is a distinction between the two ends of the needles, and also that similar ends repel each other, while dissimilar ends attract each other. The ends of the magnetized needles are commonly called poles.

Bring the marked end of the magnet which was used to magnetize the needles near to the point of either needle, suspended by its thread, and it will be found that the needle will be attracted, showing that the end of the needle last rubbed by the magnet becomes of opposite polarity to that of the end of the magnet with which it was rubbed. If the marked end is brought to the eye of the needle, repulsion will take place. The unmarked end of the magnet will be found to attract the eye of either needle and repel the point.

Hang up a magnetized needle by means of a thread passing through its centre of gravity, which should have been determined before it was magnetized, since the process of magnetization tends, as has been pointed out, to set it in a certain definite position, and therefore interferes with the determination. The needle will then set itself in a vertical plane, making a small angle with the plane of the geographical meridian, and the end of the magnet which turns towards the north will point downwards towards the ground, making an angle of between 60° and 70° with the horizon. Suppose that the marked end turns towards the north, this is then called the north, or north-seeking pole of the magnet.

If the original magnet, or either of the magnetized needles, is dipped into iron filings, it will attract them, and a number of iron filings will adhere to each end of the magnet; but it will generally be found that none will adhere to the middle.

Bring the head of a soft iron nail into contact with the marked pole of the magnet, and it will be found that as long as the iron nail is in contact with, or close to, the end of the magnet it is capable of attracting iron filings. Moreover, if one of the suspended needles is brought near to the point of the nail, the latter will be found to attract the point of the needle, and repel the eye, showing that the nail has become a magnet, and that the end in contact with the marked pole of the magnet has become a pole dissimilar to the marked pole. If a piece of hard steel were used instead of the iron nail, it would be found to be less strongly magnetized while in contact with the magnet; but on removing it from the neighborhood of the magnet it would be found to retain all its magnetism, while the soft iron nail would have lost almost every trace. The process of magnetizing a piece of iron by bringing it into the neighborhood of a magnet is called magnetic induction.

If a long steel knitting-needle is magnetized, and broken into a number of pieces, it will be found that each separate piece is a magnet, and that the ends of two pieces which were originally in contact are of opposite polarity.

This suggests, as a possible explanation of magnetic induction, the theory put forward by the German physicist, Weber. This theory has obtained general acceptance, and may now be considered as raised from the rank of an hypothesis to that of an established fact. We must first premise that a substance which is capable of experiencing any force in virtue of the magnetism of neighboring bodies is called a magnetic substance. Iron is beyond all comparison the most powerful magnetic substance. After iron, and a very long way after it, come the minerals nickel and cobalt; and the sensitive magnetic instruments which are now in the hands of investigators indicate that it is almost impossible to find any substance which is not more or less magnetic—that is to say, which is not more or less susceptible to magnetic action.

Weber supposes that every one of the molecules of which a magnetic substance is built up is itself a magnet; but that the axes of these small magnets are turned in every possible direction. The magnetic actions of the molecules will then neutralize one another, so that the body will not act as a magnet; but if either pole of a magnet be brought near to it, this pole will attract the unlike poles of the molecules, and will repel the like poles, so that the molecules will tend to arrange themselves with their north poles pointing one way and their south poles pointing the other way. The molecules will then act together, and will form a magnet with the portion nearest to the pole of the inducing magnet of unlike polarity to it. It will be of interest to consider one or two experiments which help to establish the truth of this theory.

Take an iron or steel bar—such, for example, as a poker—and hold it parallel to the direction assumed by a freely suspended magnetic needle; we should expect, if the poker were built up of magnetic molecules, that each molecule would try to set itself in a direction parallel to that of the suspended needle, for we should expect the earth to act upon each molecule in exactly the same way in which it acts upon a suspended magnet. The direction assumed by a freely suspended magnet in this part of the world is not very far removed from the vertical, so we should expect to obtain a very fairly good result by simply holding the poker in a vertical position. Now, if the poker is merely held for a few moments, either parallel to the suspended magnetic needle, or simply vertical, and then tested for magnetism by trying whether either end of it has the power of repelling either end of a suspended magnet, it will be found, provided the poker was not magnetized previous to the experiment, that it will not have acquired any sensible magnetic properties. Steel railings, however, which have remained for many years in a vertical position have frequently been observed to have acquired magnetic properties, the lower end having become a north pole, as we should expect, if Weber's theory is true. Now, it must be remembered that all the molecules of the poker are closely packed together, and it is therefore quite possible that the earth may exert a force tending to set them in a definite direction, but that this force may not be strong enough to overcome the cohesion of the molecules.

A novel application of electricity for power purposes in blast-furnace work was exhibited recently in Pittsburgh, and was notable chiefly for the extreme simplicity of the principle involved. The apparatus was nothing more than a powerful electro-magnet, designed for lifting the pigs of iron from the bed of sand in which they are cast from the furnace. The magnet somewhat resembled a bell in shape, measuring about twenty inches in height and about twenty-four inches across the bottom. The lifting capacity was rated at 7,200 pounds, or three gross tons. The magnet was attached to a crane, by which it could be lowered to the pig bed, raised with its load and transported about the cast-house. The function of the magnet was merely to do away with slings or grapples for lifting the pig-iron and to obviate the necessity of handling the pigs by hand. So far as the rapidity and ease with which a load could be attached or released are concerned, this idea certainly presents a means of economy. Its practical value, however, awaits demonstration (1891).

ELECTRICAL ENGINEERING

CHAPTER I.

CURRENT—POTENTIAL—CONDUCTORS—INSULATORS.

WHEN a stick of sealing-wax is rubbed with a piece of dry fur or flannel, the wax acquires the power of attracting to itself any light substances that may be in its vicinity. By taking suitable precautions a like power can be detected in the fur or flannel. Similar phenomena can also be produced by the rubbing together of other substances, such as glass and silk, india-rubber and silk, brown paper and a bristle clothes-brush, &c. A body which exhibits this power of attraction is said to be endowed or charged with electricity, or to be electrified.

But there are two electrical states, and this can be easily proved, for if by means of a foot or so of silk ribbon we suspend the electrified sealing-wax and bring near it another electrified stick of sealing-wax, repulsion ensues, that is to say, the suspended rod recedes from the approaching one. On the other hand, if certain necessary precautions have been taken to prevent the neutralisation or escape of the electricity that was generated on the fur or flannel rubber, it will be seen, on bringing it near the suspended sealing-wax, that attraction takes place. A similar result would follow if a warm glass rod were rubbed with a piece of dry silk and then brought near the sealing-wax. On suspending, however, the electrified glass and bringing the electrified fur near it, repulsion would take place. It is manifest, then, that as electrified glass attracts electrified sealing-wax, but is repelled by or repels electrified fur, there are two electrical states, one on the sealing-wax, which is called negative, and the other on the fur, which is called positive. It is also clear that bodies similarly electrified are mutually repellent, while bodies dissimilarly electrified are mutually attractive. This matter will again be referred to, but the point to which especial attention is now directed is that the amount of electricity developed by rubbing the two bodies—say the sealing-wax and the fur—together bears no direct relation to the amount of actual friction to which the bodies are subjected, for what is really essential in order to obtain the highest possible degree of electrification is to bring every portion of the one surface into intimate contact with every superficial particle of the other, and when that is done, no extra amount of rubbing can develop any further degree of electrification.

Speaking generally, then, it may be said that when any two bodies are rubbed together electricity is produced, although it frequently happens that the amount is so small as to render its detection very difficult. If, however, delicate apparatus, which we will not pause here to describe, is employed, very feeble charges can be indicated. In fact, if a piece of zinc and a piece of copper are simply placed in contact the feeble charge of electricity then developed can easily be rendered evident. If the same pieces of metal are placed in saline or acidulated water, a similar result follows, although in this case the water itself becomes an important factor in determining the resultant electrification. The end of the zinc outside the liquid will be found to possess properties similar to those of the sealing-wax after it has been rubbed with fur. It is, therefore, said to be negatively electrified. The copper, on the other hand, will have an electrical state similar to that of the fur itself, or of the glass which has been rubbed with silk, and it is therefore said to be positively electrified.

It follows that whether the electricity is the result of so-called friction or whether it is a consequence of the simple contact of two dissimilar bodies, it is with precisely the same *kind* of force that we have to deal, and the old distinction between 'frictional' and 'galvanic' electricity, which used to be urged with considerable persistence, is virtually a myth. The quantity of electricity may vary, and we may view it in its two phases, positive and negative, but neither of these considerations can affect the character of the force.

It may be accepted as a general fact that when the same kind of force is bestowed upon two points or bodies, but to a different extent in the one case as compared with the other, there is a universal tendency to equalise the distribution of the force—that is to say, to produce equilibrium, and this equilibrium will be established when the conditions become such as to render it possible. Reverting again to the zinc and copper plates partly immersed in water, the exposed ends will be electrified to different degrees. There will be a tendency to produce equilibrium, or, as it is more generally called, neutralisation. This will be accomplished if the necessary facilities are afforded, and until this is done the intervening space will be subjected to what may be called an electrical stress. It is found by experiment that a piece of metal affords the readiest means of relieving the strain due to this stress, thus facilitating neutralisation, for on joining the two plates together, say by a piece of copper wire, a momentary rush of electricity from the one to the other will take place. This phenomenon is that which is generally known as discharge, and it affects the whole combination, including the liquid and the metal surfaces in contact with it.

This brief spasmodic flow or rush of electricity, whose function it is to restore the electrical equilibrium, causes, however, a series of chemical changes to take place in the liquid itself, among other things a portion of the zinc being dissolved and converted into what is called a salt of that metal. These chemical reactions cause in their turn a fresh electrical difference between the plates, which is followed immediately by another equilibriating flow, and that by a further difference, and so on. These changes follow one another in exceedingly rapid succession, so rapid, in fact, that it is a matter of absolute impossibility to distinguish them separately, and we have consequently what appears to us as, and what is known as, a continuous 'current' of electricity.

A little reflection will make it evident that by following out the line of experiment and deductions here indicated, the so-called single and double fluid theories of electricity are both disregarded, not simply for the sake of disregarding them, but because they are unnecessary and involve considerations and concessions which are not warranted by the circumstances. In point of fact, electricity is not a fluid at all, and only in a few of its attributes is it at all comparable to a fluid.

Let us rather consider electricity to be a condition into which material substances are thrown, and that *all* such substances partake more or less of this condition, just as we say that all bodies are heated, although to varying degrees, and that in virtue of this heat their particles are set into more or less rapid vibration.

Moreover, as in the case of a heated body, there is a region surrounding an electrified body in which the force due to the tendency to produce electrical equilibrium can be made evident. This is shown by the fact already referred to that two bodies in a similar electrical state repel one another, while others in different electrical states attract. It is inconceivable that such an effect as the imparting of motion to a mass of matter could be produced without the aid of some medium capable of transmitting the force. What this medium actually is is a matter of doubt, and we cannot experimentally determine the question. So also is the mode or method of transmission. Under such circumstances it becomes convenient to picture to ourselves the propagation by means of *lines of force*, travelling through an infinitely elastic, imponderable medium, or substance, as it is sometimes called, which is assumed to pervade all matter and all space, and which is known as 'ether.' Granted that these lines of force may have no actual existence, the conception is, nevertheless, exceedingly useful, and facilitates an accurate estimation of the way in which electrical phenomena are set up, so much so, that the idea imperceptibly grows upon the student. and to him the lines of force become endowed with a definite meaning.

There are three features about these lines of force to which we may now draw attention. In the first place, their assumed position indicates the path along which the action takes place; secondly, their direction indicates the direction in which the force is transmitted; and, thirdly, their density, or the number occupying a given space, measures the strength or magnitude of the force. Having given to these lines of force position, direction, and density, we can predict the result which should follow in any given electrical field. For the action is always as if the lines of force endeavour to coincide in direction, and then to shorten themselves, the magnitude of the action being simply dependent upon the density of the lines.

In the case of an electrified sphere suspended somewhere in space and remote from every disturbing element, the lines of force would be radial and equidistant in position, their density would depend upon the degree of the electrification or the quantity of the charge, while their direction, that is, radially inwards or radially outwards, would depend upon whether the charge were negative or positive.

Let us assume a positively charged sphere to be suspended, with its lines of force directed outwards, and a second sphere, negatively charged, with its inwardly directed lines of force, to be brought into the vicinity of the first sphere; it will be evident that many of the lines of force of the two spheres will bend or turn round and concentrate themselves within the space intervening between the spheres. The lines of force will now be similar in direction, and, owing to the shortening tendency above referred to, attraction results.

The attraction, presuming it to be sufficiently strong, will impart motion to one or both of the spheres, or, in other words, work will be performed. Now this capacity for doing work arises solely from the electrification, and the quantity of work performed is proportional to the degree of electrification. But 'capacity for doing work' and 'potential' are convertible terms—that is to say, anything which possesses the capacity for doing work is said to have a certain potential, consequently the degree of electrification of any body is known as its potential. We have previously said that the tendency to produce, between two electrified points or bodies, a state of electrical equilibrium, is proportional to the difference of their degrees of electrification. In technical language this means proportional to their difference of electrical potentials. Therefore, in the case of the zinc and copper plates immersed in acidulated water, the flow of electricity from the exposed end of the copper to the exposed end of the zinc is correctly described as being due to a difference of potential between those ends.

If the student has grasped what has already been said, he will be able to readily apply the doctrine of potential to special cases; for example, it will be evident that no two parts of the same body (providing it is one that can transmit or propagate the flow of electricity) can remain for any length of time at different potentials, for the moment a difference of potential is established an electrical stress is set up, and the flow of electricity follows as a necessary or natural consequence. On the other hand, where there is no difference of potential there can be no flow of electricity. So that we come to these conclusions—viz. that electricity always flows between two bodies which are at different potentials; that it flows from the body possessing the higher to that possessing the lower potential; that in the case of the 'current' maintained by the 'simple cell,' composed of zinc and copper plates dipping into acidulated water and described in a previous page, we had a difference of potential established on the zinc and copper extremities; that on joining these extremities together there was a flow of electricity to produce equilibrium; that this, by means of the chemical changes, re-established a potential difference; and that these actions and reactions, being alternated with infinite rapidity, appear to us as a continuous current.

We may, therefore, define a 'current' as the expression of an effort ever being made to establish electrical equilibrium between two points which are ever being electrified to different potentials. Neither of these objects is attained—that is to say, a difference of potential is never permanently established on the one hand, and, on the other, equilibrium it is impossible to maintain.

Let us further consider the case of the simple cell, the zinc and copper of which, however, instead of being joined together, are each connected to long pieces of wire, whose other or free extremities are inserted in the earth at different places. It used to be the general assumption that in this case the current would flow from the copper plate to the earth, and through the earth to the other wire, up which it would pass and so return by the zinc to the battery. But anything more unreasonable than such an hypothesis it is really impossible to conceive. To demonstrate this we need only take into consideration the state of affairs at the Central Telegraph Office in London, where there are 1,000 different circuits or lines, one end of each battery being joined to the same earth plate under the office, the other ends being joined to the respective lines, which in their turn are joined to earth plates at the distant ends. Viewed in its real aspect, this 'earth-return' theory compels the assumption that the 1,000 currents which go to earth at as many different places—some at Newcastle, some at Liverpool, others at Cardiff, Yarmouth, &c., others, again, only a few hundred yards away in several of the City thoroughfares—all return through the earth to the earth plate or connection under the Central Office, where each individual current has to pass the other 999 currents travelling through the plate, and single out the particular wire joined to the particular battery from the other end of which it emanated, and is not satisfied or has not completed its work until it thus gets safely home again. It will readily be seen that, if such were actually the state of affairs, the laws above stated, that electricity only flows under a difference of potential and always flows when there is that difference, would be nullified.

Like everything else in the universe, the earth itself is always more or less electrified, and, as a consequence, it is always at a certain potential. It will therefore be seen that, were a body which had been electrified to a higher potential than the earth to be connected with the earth, a flow of electricity would take place passing from that body to the earth, so that both the body and earth assume the same potential, and it may be mentioned that the passage of this flow could be easily observed by the introduction of certain apparatus. On the other hand, were a body to be electrified to a potential lower than that of the earth and to be connected with it, a flow of electricity would be determined between the earth and the body, and the passage of this electricity could also be rendered evident. Consequently, when copper and zinc strips are immersed in acidulated water and the exposed ends become electrified, the one to a higher and the other to a lower potential than the earth, the connection of those extremities with the earth causes a flow of electricity from the plate of higher potential to the earth, and from the earth to the plate of lower potential. These flows will be equivalent to joining the plates directly together and so releasing the electrical stress.

Thus is it with every battery: the potential of the earth is above that of one end of the battery and below that of the other end. There is then no need for a current to flow between the two earth-connections, and the assumption of such a state of affairs is quite gratuitous. It must not, however, be supposed that the flow of electricity from or to the earth can sensibly affect its charge or potential, the terrestrial charge as a whole being so enormous as to make any other charge or potential incomparably feeble and insignificant. To make this clearer we will employ an analogy. Let us suppose that we have two tanks containing water, the bottom of one being placed ten feet above the level of the ocean, and the other, which we will suppose to be very deep, immersed until the surface of the contained water is ten feet below the ocean level. If now we suppose holes to be made in the bottoms of the tanks, all the water will flow out of the higher tank into the sea below, while water will flow up into the lower one until the ocean level is reached. But of course no one would contend that these changes would make any difference in the level of the surrounding waters. even if more water were received from the higher tank than was given to the lower, and what is true in this case is equally true in the case of electricity. In fact, the earth is a body whose capacity for electricity, so far as we are concerned, is infinite, and nothing that we can do can alter its charge. The man who would assert that when he joins one end of his battery to earth, say, at London, and the other end to earth, say, at Aberdeen, and that in consequence a current flows through the earth from one connection to the other, asserts, in fact, although he may not know the significance of his contention, that he places these two points in London and Aberdeen at different electrical potentials. He might as reasonably contend that if he turns on his water-tap into the Thames at London and digs a hole in the bank of the river at Windsor, he sets up a difference of level between the two places, and causes the water which he pours in at London to travel up against the stream and fall out at Windsor.

We come now to a real difficulty a solution of which is improbable, although it is, perhaps, in the future not impossible—and that is, to be able to say with certainty in which direction a current really travels, or, in other words, to declare which of two differently electrified bodies has the higher, and which the lower potential. All we can say with any certainty is that there is a difference of potential, and that therefore the current flows from the point of higher to that of lower potential. It is usual to assume, in the present incomplete and imperfect state of our knowledge concerning the nature and propagation of electricity, that the electric state which we know as positive has a higher potential than that state which we know as negative, whence we say, or assume, that electricity flows *from* a positively electrified *to* a negatively electrified body. And we will in this work follow this assumption, true or otherwise, as it involves no sacrifice of principles, notwithstanding the fact that experiments have been performed which tend to show that that state which we call negative is really of higher potential than that which we call positive.

Reference has several times been made to the use of wire as a means of connection between two oppositely electrified bodies, or between two bodies at different potentials. Were we desirous of transmitting mechanical instead of electrical energy, a hempen or silken cord would answer equally well, if due provision had been made that the cord should have the requisite mechanical strength or tenacity to transmit the energy without fracture. But tenacity is not the necessary attribute for a body to possess in order that electricity may be readily propagated through it. All substances admit of this transmission, although to very varying degrees. A piece of copper wire offers greater facilities than a piece of iron wire of similar dimensions, which in turn offers greater facilities than a similar piece of German-silver wire. But the metals one and all are enormously superior in this respect to the great bulk of non-metallic substances. On the other hand, every substance, whatever its nature, offers a greater or less amount of resistance to the transmission of electricity. Bodies which offer little resistance to the electric flow are said to be good conductors, while those which offer considerable resistance are said to be bad conductors or insulators. To the former class belong the metals, carbon, ordinary water, &c., the latter class including such substances as glass, air, sulphur, resin, india-rubber, and ebonite. Between these two classes are many substances which might be included in either class, but no hard and fast line can be drawn.

It has been shown that the result of joining directly together two bodies electrified to different potentials is a flow of electricity from the body charged to the higher potential, to that charged to the lower until electrical equilibrium between the two bodies is obtained. And a similar result follows if we join the bodies together by a piece of wire; while if they have only air or some other bad-conducting substance separating them, there will be no flow at all, or only a very feeble one. If the path of the flow is made longer, or more difficult, say by the interposition of a longer or poorer conductor, it naturally follows that the time which is taken for equilibrium to be restored is lengthened, and the rate of restoration, that is, the strength of the current, is less. But if the potential difference and the quantity of electricity transferred is the same in the two cases, the energy expended in the effort to restore equilibrium is the same.

The result, then, of interposing a substance of poorer conducting power, or, what amounts to the same thing, of higher resistance, between two bodies having a potential difference, is to reduce the strength of the flow or current passing from the one to the other. We can find a very simple analogy to this if we suppose two tanks of water at different heights one directly above the other. So long as the bottom of the higher one is intact the resistance to the flow of water from it to the other is practically infinite, but if we interpose a relatively bad conductor of the water in the form of a very small pipe or tube between the water in the tanks, there will be a correspondingly weak or feeble flow of water from the higher to the lower tank. If we increase the size or bore of the pipe, the conducting power will be increased proportionally, and a corresponding increase in the volume of the water (or in the strength of the current) flowing will be observed. Pursuing this to its finality, if the bottom of the upper tank is removed instantaneously there will result an equally instantaneous fall of the whole of the water in the tank. Such a state of things can easily be traced between two bodies charged to different electrical potentials and connected by various substances whose conducting powers range from the almost infinitely great to the almost infinitely small, or, in other words, by varying the amount of resistance which is here shown to be the converse or reciprocal of conductivity, we can, in a corresponding value, vary the strength of the current.

To summarise our observations on the question of resistance, we may say that if we electrify two bodies, connected only by the air, to different potentials, we subject the intervening air to a species of stress. If we very considerably increase the potential, the air being no longer able to sustain the stress, a discharge or an electric flow ensues. A similar result can be achieved, without increasing the potential difference, by reducing the distance between the electrified bodies, or by bridging over the air-space with a piece of wire or other good conductor. In either case the ability to sustain the stress is reduced, and we call this ability to sustain the stress resistance. The more resistance we insert between the electrified points or bodies, the more do we thereby reduce or prevent the flow of electricity.

CHAPTER II.

PRACTICAL UNITS—OHM'S LAW—C.G.S. SYSTEM.

IN dealing, in the previous chapter, with the general attributes of electricity, the only degree of comparison arrived at was to say that one electrification, resistance, or current was greater or less than another. And to a somewhat considerable extent this was, until within the last few years, deemed sufficient. It is, however, now essential that more precision in comparing or measuring forces and their properties and effects should be obtained. Measurement is, in fact, the most important branch of electrical science, as, indeed, it is of every other physical science.

Instead of simply saying that one lump of iron is heavier or weightier than another, it is usual to say by how much they differ. Thus one lump may have a mass of ten pounds, and another a mass of twenty pounds. The latter is therefore ten pounds heavier than the former. We have here introduced a unit of measurement, viz. the pound, or unit of mass. Similarly, the inch or foot may be used as a unit of length, the second as a unit of time, the pint as a unit of capacity, the sovereign as a unit of coinage, and so on. These units are all such as everybody can readily appreciate. They are so frequently employed that no mental effort is required to understand what is meant when any one of them is mentioned.

In dealing with electricity the first thing we wish to measure is naturally the amount of the electrical difference between two bodies which causes an electrical stress and which may result in a current of electricity. But we are confronted with two difficulties. The first is that by none of the everyday units—by no unit employed for any other purpose—are we able to indicate exactly the electric potential in a body. Moreover, electricity being but a condition of matter, and not matter itself, it is impossible to measure it directly. We can only measure it by its effect upon material substances. In the next place, inasmuch as it is impossible to obtain or even to conceive of a body altogether devoid of electrification (although it is not always perceptible), it is impossible to fix on an absolute zero potential, and measure potentials from that point; in just the same way that it is impossible to have a zero level, some arbitrary point such as the sea-level at high tide having to be employed if we wish to measure the relative height of two or more points. It is, consequently, necessary to look elsewhere for a starting-point, and to fix on a convenient arbitrary potential zero. We take as a zero the potential of the earth's surface, and bodies which are said to be positively electrified are at a higher potential than the earth, while negatively electrified bodies are at a lower potential. Positive and negative potentials may therefore be said to correspond to height and depth in their relation to the sea-level. Inasmuch, however, as we are unable to detect any potential at all unless we take two points or bodies whose potentials are different, the measurement of potential itself again presents difficulties. On the other hand, when we are called upon to measure the potentials of two bodies, what we really desire to know is the difference between those potentials; or, if we call the potential of one body P, and that of the other P_1, we want to know the value of $P-P_1$; for, after all, it is this difference of potential that determines the flow of electricity. This difference of potential is known as electro-motive force, which is frequently contracted into the initials E.M.F., or, shorter still, into E. only. It is this electro-motive force, then, that we desire to measure, and the practical unit by which it is measured is known as the 'volt.' We will, for the present, rest satisfied with the simple statement that the volt is approximately equal to, although actually a fraction less than, the electro-motive force of a single Daniell cell. (See Chapter III.)

Reference was made in the previous chapter to 'resistance,' and it was described as the converse of conductivity, which again we described as the ability of a body to transmit a current of electricity. It is easy to show that resistance may be expressed as a ratio —the ratio of electro-motive force to current—and many authorities insist that it should always be regarded thus It may also be expressed as a 'velocity,' or the ratio of length to time, but we prefer to deal with it as it appeals to practical electricians—viz. as an attribute of matter, varying with different substances, and in virtue of which such matter opposes or resists the passage of electricity, whence the current has to do 'work' or expend 'energy' in effecting the passage. The law of the conservation of energy teaches us that force is indestructible, and it follows, therefore, that if energy has to be expended in impelling a flow of electricity against a greater or less amount of resistance, the equivalent of that energy must be developed in some other form. This other form is usually heat; or, in other words, when a body opposes a certain amount of resistance to the passage of electricity, heat is produced, the actual amount of heat being an exact counterpart of the energy expended in overcoming the resistance, and varying therefore directly as that resistance. Consequently, if we have two conductors, the resistance of one of which is twice that of the other, and if we send currents of equal strength through both wires, twice as much heat will be developed in the conductor of the higher resistance as will be developed in that offering the lower resistance. We shall have occasion to deal with this subject more fully in a future chapter, but we may add here, that if we wish to perform work at any point by means of an electric current conducted by a wire to that point, we must keep the resistance of that wire down to the lowest practical limit, because every fraction of the energy frittered away in heating the conductor means so much less energy available for the particular work which we wish the current to perform. It is apparent, then, that we require a unit by which we shall be able to compare the resistances of various substances, and the unit selected is called the 'ohm.' It was decided by an International Congress of Electricians which assembled in Paris in 1884 as being equal to the resistance which is offered to the flow of electricity by a column of mercury one square millimetre (0·93937 of an inch, or a small fraction less than $\frac{1}{25}$ of an inch) in section, and 106 centimetres long (the centimetre is equal to 0·3937 of an inch), the temperature being at the freezing point (32° Fahrenheit or 0° Centigrade), and the pressure of the air equal to the pressure at the base of a column of mercury 30 inches, or 760 millimetres, in height. The Congress which determined the value of this unit also decided that it should be known as the 'legal' ohm. A millionth part of this unit is called a microhm, and one million ohms a megohm.

There have, in the past, been an almost unlimited number of units, more or less crude and unreliable; for it must be borne in mind that for a unit to be of any real value it must be permanent or durable, it must be capable of confirmation, and its derivation must be well known and invariable. One of the earlier units of resistance was that offered by a mile of the then best procurable iron wire of a certain gauge or diameter. The indefiniteness of such a unit may be conceived when it is called to mind that even now no two samples of the same wire will offer the same resistance; and still more so was this true a few years ago, when the quality of iron wire as a conductor was vastly inferior compared with what it now is, both as regards its actual resistance and its uniformity.

The only other unit which we need consider is that known as the B.A., or British Association Unit. It was determined in London in 1863 by a committee appointed for the purpose by the British Association, and the method of determination then adopted was the basis upon which the Paris or legal ohm was afterwards calculated. These units are both based on what is called the C.G.S. system (p. 40), the Paris unit being really a correction of the B.A. unit. The practical standard of the former has, however, a great advantage over that of the latter, which consisted of the resistance of a certain length of wire carefully preserved in London. This was, of course, rarely used, and duplicates of the standard had to be employed for comparing or standardising other resistances. The legal ohm is manifestly capable of being reproduced more easily, and it is this fact which imparts to it its chief value. The B.A. unit is a fraction smaller than the Paris ohm, the actual proportion being 0·986 to 1·0. If it were possible at the present day to universally adopt a common unit, it would certainly be a great advantage, for then everybody would know what was meant when anybody else mentioned any particular resistance. But prior to 1884 a vast quantity of electrical apparatus and machinery was in use, and everything in England and some other countries was measured by the B.A. unit, while the measurements employed on the Continent were for the most part referrible to the Siemens unit, which was the resistance of a column of mercury 1 metre (or 39·37 inches) long, the other details as to its size, temperature, and pressure being the same as those employed in devising the legal ohm. As it was, the various administrations and authorities were placed in a most unpleasant dilemma. If they re-standardised and re-marked all their existing apparatus they would have had to incur enormous expense, while if they continued the use of their existing standards they would be perpetuating an inconvenience which they had called the Congress together to remove. In the majority of cases, questions of finance compelled them to adopt the latter alternative, so that with us, most telegraph apparatus continues to be measured by the B.A. unit, while the apparatus employed in the newer industries, such as electric lighting, is measured by the legal ohm. Accordingly, in this work we shall endeavour to keep the latter in view.

The student will frequently come across the expression 'specific resistance,' and it is a most important term. It may be defined as the resistance of any particular substance as compared with the resistance of a piece of some other conductor, such as silver, of similar dimensions, the test being made under similar conditions. It is a matter of great convenience that different bodies vary in their relative or specific resistances, for there are times when we want the lowest possible resistance, while at other times we require a large measure of resistance, more particularly when we desire to prevent an electric discharge, to prevent the flow of an electric current, or to prevent electricity leaking from one body to another. Appended is a table based upon that of Dr. Matthiessen which shows the relative resistance of a number of metals frequently met with, and as the variation of the temperature of a body varies its electrical resistance, all the tests have been taken at a common temperature, viz. that of freezing point, or the necessary corrections made to correspond to that temperature.

An alloy of copper, nickel, and zinc (the usual constituents of German silver), combined with 1 or 2 per cent. of tungsten, was introduced a few years ago under the name of platinoid. It is found that the addition of tungsten imparts greater density to alloys

TABLE SHOWING RELATIVE RESISTANCES OF CHEMICALLY PURE SUBSTANCES AT 0° C. IN LEGAL OR PARIS OHMS.

Name of Metal	Relative Resistance	Resistance of a wire 1 foot long, $\frac{1}{1000}$ of an inch in diameter	Resistance of a wire 1 metre long, 1 millimetre in diameter	Resistance in microhms	
				Cubic inch	Cubic centimetre
Silver, annealed . .	1·000	9·048	0·01916	0·5921	1·504
Copper, annealed . .	1·063	9·612	0·02034	0·6292	1·598
Silver, hard drawn . .	1·086	9·830	0·02080	0·6433	1·634
Copper, hard drawn .	1·086	9·831	0·02081	0·6433	1·634
Gold, annealed . .	1·369	12·38	0·02620	0·8102	2·058
Gold, hard drawn . .	1·393	12·60	0·02668	0·8247	2·094
Aluminium, annealed .	1·935	17·53	0·03710	1·147	2·912
Zinc, pressed . . .	3·741	33·85	0·07163	2·215	5·626
Platinum, annealed .	6·022	54·49	0·1153	3·565	9·057
Iron, annealed . .	6·460	58·45	0·1237	3·825	9·716
Lead, pressed . .	13·05	—	0·2498	7·728	19·63
German silver, hard or annealed . . .	13·92	125·91	0·2666	8·240	20·93
Platinum, silver alloy ($\frac{1}{3}$ platinum $\frac{2}{3}$ silver) hard or annealed . .	16·21	146·70	0·3106	9·603	24·39
Mercury . . .	62·73	572·30	1·211	37·15	94·32

and reduces any tendency to oxidation. When polished, the alloy is scarcely distinguishable in appearance from silver. A cubic centimetre offers a resistance ranging from about 30 to 36 microhms, so that its resistance is about one and a half times that of German silver. As, however, alloys always vary more or less in their composition, a definite resistance cannot safely be assigned to any commercial variety, and calculations concerning them can only be accepted as actually true of the particular samples tested. Platinoid, when drawn hard, is, like copper, softened by heating and sudden cooling.

The admixture of even a minute proportion of foreign matter very considerably reduces the conductivity or increases the resistance of a metal. A very remarkable effect is observed when an alloy of two or more metals is tested, for the specific or relative resistance of the alloy will always be found higher than that of either of its constituents. Purity in the case of simple substance, and absolute uniformity in the constitution of alloys, such as German silver, is, therefore, pre-eminently essential, if the highest conductivity or if a certain specific resistance is desired, as is shown by the following table, giving the specific conductivities of various samples of copper.

TABLE SHOWING THE COMPARATIVE CONDUCTIVITY OF PURE COPPER AND THE BAR COPPER OF COMMERCE.[1]

(All the wires were annealed.)

	Conducting power.
Pure copper	100·0 at 15·5° C.
Lake Superior, native, not fused	98·8 at 15·5° C.
Ditto, fused, as it comes in commerce	92·6 at 15·0° C.
Burra Burra	88·7 at 14·0° C.
Best selected	81·3 at 14·2° C.
Bright copper wire	72·2 at 15·7° C.
Tough copper	71·0 at 17·3° C.
Demidoff	59·3 at 12·7° C.
Rio Tinto	14·2 at 14·8° C.

Or, again, if the relative conductivity of pure copper is taken as 100, then that of copper mixed with 1·6 per cent. in volume of silver will be only 65; while the conductivity of silver mixed with 1·2 per cent. in volume of gold will be 59 when that of pure silver is taken as 100.

A highly interesting phenomenon is the wonderful effect which a variation in temperature produces upon the resistance of the various substances through which a current may flow. The effect would be less surprising were it general or were it consistently uniform in all bodies, but the great feature to be observed is that while in the case of metals the resistance of a conductor invariably increases with an exaltation in temperature, the non-metals all show a decrease in resistance under similar circumstances. It is also a remarkable feature that in the case of metals the variation is much less in alloys than in pure metals. These results are fraught with the greatest importance, as they limit considerably the number of substances available for many classes of electrical apparatus. For example wires which are to be employed as standards for comparing or measuring resistances should have as nearly as possible the same value at all temperatures. It may be observed that the insulating coatings of the wires in the telegraph cables laid in such waters as the Indian Ocean show a marked decrease in their insulating properties after submergence, consequent upon the fact that the water is several degrees warmer than that in the tanks in which the standardising tests were made. The accompanying table, showing the percentage variation in the resistance of various bodies between the temperature of freezing water and that of boiling water, should prove eminently interesting. It is certainly useful and important.

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[1] Report of the Government Submarine Cable Committee.

Name of Metal	Conducting power at 0° C. Silver = 100	Percentage fall of conducting power between 0° and 100° C.
Pure iron	16.81	39.2
Pure thallium	9.16	31.4
Other pure metals in a solid state . .	—	29.3
Gold with 15 p.c. iron	2.76	27.9
Proof gold	72.55	26.4
Standard silver	80.63	23.2
Gun metal (Austrian)	27.08	18.3
Copper with 25 p.c. platinum . . .	22.08	11.5
Silver with 5 p.c. platinum	31.64	11.3
Silver with 9.8 p.c. platinum . . .	18.04	7.1
Copper with 9.7 p.c. tin	12.19	6.6
Gold silver alloy	15.03	6.5
Platinum with 33.4 p.c. iridium . .	4.54	5.9
German silver	7.80	4.4
Gold with 4.7 p.c. iron	2.37	3.8
Silver with 25 p.c. palladium . . .	8.52	3.4
Silver with 33.4 p.c. platinum . . .	6.70	3.1
Platinoid	—	2.09

As may have been gathered from what has already been said, when we increase the length of a conductor we invariably increase its resistance. This follows as a matter of course from the fact that if we urge a certain current through a wire of increased length, we give it more work to do, necessitating, consequently, a greater expenditure of energy in precisely the same way that a railway engine would consume more coal in taking a train a distance of 200 miles than it would consume in taking it only half that distance. The resistance of a conductor of uniform material and thickness or cross-section varies directly as its length—that is to say, if we vary the length of the conductor we vary its resistance at exactly the same rate, or, in fewer words, resistance varies directly as the length of the conductor. If a mile of wire of a certain gauge offers a resistance of ten ohms, two miles of the same wire would offer twenty ohms.

The effect of increasing the size or sectional area of a conductor is to increase its conductivity and, consequently, to diminish its resistance, in exactly the same way that increasing the diameter of a pipe increases the amount of gas or water that can be passed through it. The resistance of a conductor varies inversely as its sectional area. That is, if we have two conductors, such as two specimens of copper wire, drawn from the same bar, the amount of resistance which the wires will offer depends upon the size of the wires or on the area of the ends exposed on cleanly cutting them at right angles to their length—that is to say, upon the amount of metal through which the current can flow. Most wires are round, so that the section is a circle, and it becomes necessary to understand the method of comparing the areas of circles. The area of a circle varies as the square of its diameter; for example, if we have two circles, one having a diameter of one-tenth of an inch and the other of two-tenths of an inch, their areas or the spaces they enclose will not be in the proportion 1 : 2, but as the squares of those figures, viz. 1 : 4, so that one wire which is twice the diameter of another, other things being the same, only offers one quarter of the resistance offered by the thin wire. While if we treble the diameter of the wire, or make it three-tenths of an inch, the resistance will be only one-ninth of that of the thinnest wire. As a matter of fact, the thickest of these three wires will weigh exactly nine times as much as the thinnest, there being nine times as much metal in it. We may, therefore, state our law in other words by saying that the resistance of wires uniform in all particulars excepting thickness varies inversely as their weight. Thus, if a mile of copper wire weighs 100 lbs. and has a resistance of 9 ohms and an equal length of similar copper wire weighs 150 lbs. the resistance of the latter will be 6 ohms. Again, the specific resistances of iron and copper are approximately as 6 to 1. If, now, a mile of iron wire, 0·240 of an inch in diameter, has a resistance of 5 ohms, and it is thought for certain reasons desirable to substitute a mile of copper wire having the same resistance, we should have to use wire weighing one-sixth the weight of, or whose sectional area would be one sixth of, that of a copper wire 0·240 of an inch in diameter, because the resistance of a mile of the latter would be only five-sixths of an ohm. The required thickness could be ascertained by rule of three, for if x stands for the required diameter,

$$6 : 1 :: (0{\cdot}240)^2 : x^2,$$

from which we find $x^2 = 0{\cdot}0096$. Therefore x, or the required diameter, is equal to the square root of 0·0096, or 0·098 of an inch nearly.

A conductor offers to the passage of electricity at equal temperatures a constant resistance which is altogether independent either of the electro-motive force or of the strength of the current. That is to say, a wire which offers 10 ohms to the passage of a feeble current, offers precisely the same resistance to a powerful current, except in so far as an increase in the strength of the current involves a corresponding increase in the temperature of the wire, and this increased temperature causes a proportionately increased resistance, as already pointed out.

We come now to the consideration of the laws which determine the strength of a current and of the relationship subsisting between strength and the other attributes of an electric current. The real relationship can, perhaps, be best understood by the aid of a simile. Let us suppose two tanks, one very high up, say three or four hundred feet above the ground, the other raised only a few feet. Let both tanks contain the same quantity of water, and let both of them be supplied with pipes, the one for the upper tank being, however, very much smaller in diameter than that for the lower. On turning the taps the water from the upper tank, although small in quantity,* will issue forth with much greater force than that from the lower tank, although the quantity or rate of flow from the lower tank may considerably exceed that from the upper tank. In other words, the pressure in the long small pipe is much greater than in the short but large one, while the quantity of water delivered by the former is considerably less than that delivered by the latter. Pressure in a column of water corresponds with the electro-motive force of a battery, while the volume or quantity of water flowing through the pipe corresponds to current strength. But to pursue the analogy still farther, if the upper tank be raised sufficiently high, the greater pressure so obtained will augment the velocity of the water, and the two tanks will be emptied in the same time. There are two things, then, that govern the quantity of water delivered or the rate of delivery—viz. the pressure, and the size of the pipe, which latter corresponds in electrical considerations with the size of the conductor and consequently with the resistance.

By current strength is meant, therefore, *the amount or volume of electricity passing any point in a circuit at any particular moment.* It corresponds to the rate of delivery of gas or water by a pipe. In a simple circuit it depends upon two things, the electro-motive force of the generator or battery and the resistance of the whole circuit, which comprises the wire and apparatus as well as the battery itself. The practical unit of current strength or rate of delivery is called the ampere, and is that amount of current which is urged through a circuit of one ohm resistance by an electro-motive force of one volt. If this current is maintained for one second, one unit of electrical *quantity* is delivered and this unit is called the coulomb. If a current of half an ampere flows for two seconds, the quantity of electricity delivered is again one coulomb. So also is it if a current of two amperes flows for half a second, so that in every case the rate of flow, or current strength in amperes multiplied into the time in seconds gives us the total quantity of electricity or the number of coulombs. Thus if Q represents the quantity of electricity in coulombs, C the current strength in amperes, and t the time in seconds,

$$\mathrm{Q} = \mathrm{C} \times t.$$

As the quantity of electricity delivered is rarely required to be known, but rather the rate of delivery or flowing, we will deal more fully with the method of ascertaining this rate. In order that this may be more readily understood, we will at once proceed to the discussion of 'Ohm's Law,' which declares that *the current strength varies directly as the electro-motive force, and inversely as the resistance.* This law may be represented by the simple equation—

$$\frac{\text{Electro-motive force}}{\text{Resistance}} = \text{current strength},$$

or,
$$\frac{E}{R} = C.$$

As an example of the relation which the units bear to each other we may take the simple case of a battery having an electro-motive force of one volt and sending a current through a circuit whose total resistance is one ohm. The current strength will then be one ampere, thus :—

$$\frac{1 \text{ volt}}{1 \text{ ohm}} = 1 \text{ ampere},$$

and if this current is maintained for one second, one coulomb of electricity will have passed. By doubling the resistance, we get

$$\frac{1 \text{ volt}}{2 \text{ ohms}} = 0{\cdot}5 \text{ ampère}.$$

Similarly, by doubling the electro-motive force we get, with unit resistance,

$$\frac{2 \text{ volts}}{1 \text{ ohm}} = 2 \text{ amperes}.$$

A little reflection will make evident the subsidiary law that *the current strength is the same in all parts of the circuit*, and does not in any sense vary in different parts of the same circuit. The current strength can easily be supposed to be uniform in a uniform conductor, but if we make up a circuit with wires of different degrees of conductivity, or if we interpose any liquid conductor, the same law holds good, just as would be the case if we were to urge a current of water through a pipe of variable diameter. It is manifest that if a gallon of water enters the pipe in a certain time the same volume must pass out in the same time (supposing the pipe to have been already full), and the same volume must pass every point in the pipe in the same interval of time, although in the thinner or smaller portions of the pipe the water travels faster and generates a little more heat by friction with the sides of the pipe than in the larger sections of it. This latter analogy also holds good with regard to electricity, the thinner wire or poorer conductor will be more highly heated than the thicker or better conductor. It is this fact that makes electric lighting by incandescent lamps possible. It is doubtful whether in the whole range or history of electrical science a law has ever been enunciated so full of truth and of such truly immense importance as that discovered by George Simon Ohm, and we shall find frequent need to refer to it in the succeeding chapters.

For the benefit of those, and our experience teaches us that they are very numerous, who do not understand the full meaning of a simple equation, we may say that if

$$\frac{E}{R} = C, \text{ then } \frac{E}{C} = R, \text{ and}$$
$$E = RC \text{ (or } R \times C\text{)}.$$

So that, if, of these three quantities, we are told two, we can always readily calculate the third. Thus, with a current of two amperes and an electro-motive force of 10 volts, the resistance will be

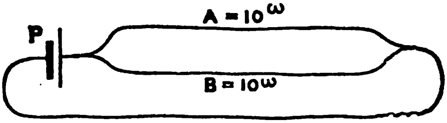
$$\frac{10}{2} = 5 \text{ ohms.}$$

Similarly, if a current of 5 amperes flows through a resistance of 10 ohms, the electro-motive force capable of maintaining this current will be

$$10 \times 5 = 50 \text{ volts.}$$

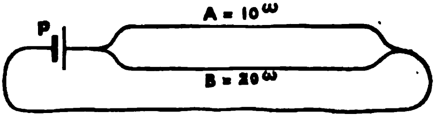
When two or more channels or paths are open to a current of electricity, the current divides between them, just as water or gas in a pipe will divide into any number of branch pipes. If in the case of electrical conductors there are two wires (A and B, fig. 1), between which the current can divide, and if the resistances of the two wires are equal, the current will divide equally between them ; thus, if a current of two amperes flows from the battery P, one ampere will go through each wire. When

FIG. 1.



the resistances are not equal, the current will divide inversely as the resistances; thus, if the resistance of one wire (A, fig. 2) is 10 ohms, and of another (B) is 20 ohms, and a current of three amperes divides between them, two amperes will go through the wire A of 10 ohms and one ampere through the wire B of 20 ohms.

FIG. 2.



When two or more wires are joined together so that the current divides between them, they are said to be joined up in 'parallel,' and when the end of one is joined to the end of another so that the whole current goes through both wires, one after the other, the wires are said to be joined up in 'series.'

The law for double channels holds equally good for multiple channels. Thus, if there are 10 wires of uniform resistance and a current of 10 amperes divides between them, it will do so equally, so that one ampere will flow through each wire. When the resistances vary, then the current flowing through each wire will vary also, but in the inverse ratio.

When, however, two or more wires are joined up in parallel, a serious alteration is made in the condition of the circuit, for the total amount of current that is produced, whether it be from a primary battery, a dynamo-electric machine, or any other source of electrical energy, will be increased. This increase follows from the fact that when wires are joined up in parallel, their united, or, technically speaking, their joint resistance is less than that of any one of the wires taken separately. The meaning of this will be more readily apparent if a wire is regarded as a conductor rather than as a source of resistance. Thus, if two equal wires lie side by side and the current is allowed to flow through them, the conducting power of the double wire will be twice that of either wire taken separately, in precisely the same way that a water or gas-pipe two square inches in section will transmit twice as much as a similar pipe only one square inch in section. If, therefore, the

conductivity of the two wires in parallel is twice that of one of them, their united or joint resistance will be only half that of one of them. Thus, if two wires, each of 100 ohms resistance, are joined to a battery in parallel, their joint resistance will be 50 ohms. Similarly, if ten wires, each of 100 ohms resistance, are joined in parallel, they will offer a joint resistance of 10 ohms. We can, therefore, say that if any number of wires (n) of uniform resistance (R) are joined in parallel, or 'multiple arc,' as the arrangement is sometimes called, then their joint resistance $= \frac{R}{n}$.
Suppose, now, that our battery has an electro-motive force of 100 volts, and that its internal resistance is negligibly low, with one wire of 100 ohms joined on we get

$$\frac{100 \text{ volts}}{100 \text{ ohms}} = 1 \text{ ampere.}$$

With two wires we get—

$$\frac{100 \text{ volts}}{\frac{100}{2} \text{ ohms}} = \frac{100}{50} = 2 \text{ amperes.}$$

This current divides equally between the two wires, one ampere going through each.

With 10 wires we get—

$$\frac{100 \text{ volts}}{\frac{100}{10} \text{ ohms}} = \frac{100}{10} = 10 \text{ amperes.}$$

Whence one ampere will still go through each wire, so that the strength of the current increases in precisely the same proportion as the number of wires. If, however, the internal resistance of the battery is proportionally high enough to necessitate its being taken into account, the reduction of the external resistance will not produce so marked an effect. With a battery resistance of 100 ohms and a single wire of a like resistance we get

$$\frac{100}{100 + 100} = \frac{100}{200} = 0{\cdot}5 \text{ ampere}$$

and when two wires are joined in parallel we get—

$$\frac{100}{100 + 50} = \frac{100}{150} = 0{\cdot}66 \text{ ampere.}$$

With 10 wires we get

$$\frac{100}{100 + 10} = \frac{100}{110} = 0{\cdot}90 \text{ ampere.}$$

Thus with two wires in parallel a current of 0·33 ampere would flow through each wire, while with ten wires the current strength in each wire would be only 0·09 ampere.

When the parallel circuits are of different resistance, the calculation of their joint resistance involves a little more trouble. Let us suppose two wires joined in parallel, their individual resistances being R_1 and R_2 respectively. As we have already pointed out, resistance is the converse of conductivity. Therefore, R_1 and R_2, representing the resistances, $\frac{1}{R_1}$ and $\frac{1}{R_2}$, will represent their conductivities, whence the united conductivity will be $\frac{1}{R_1} + \frac{1}{R_2}$, which is equal to $\frac{R_1 + R_2}{R_1 R_2}$. This being the joint conductivity, the joint resistance will be $\frac{R_1 R_2}{R_1 + R_2}$; thus if $R_1 = 500$ ohms and $R_2 = 1{,}000$ ohms, their joint resistance will be

$$\frac{500 \times 1000}{500 + 1000} = \frac{500{,}000}{1{,}500} = 333{\cdot}3 \text{ ohms.}$$

Briefly put, it may be said that the joint resistance of any two conductors is equal to the product of those resistances, divided by their sum.

Similarly with three (or more) wires of different resistances, their joint conductivity would be

$$\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} = \frac{R_1 R_2 + R_2 R_3 + R_1 R_3}{R_1 R_2 R_3},$$

whence the joint resistance will be

$$\frac{R_1 R_2 R_3}{R_1 R_2 + R_2 R_3 + R_1 R_3}$$

If R_1, R_2 and R_3 are 500, 1,000, and 2,000 ohms respectively their joint resistance will therefore be

$$\frac{500 \times 1{,}000 \times 2{,}000}{(500 \times 1{,}000) + (1{,}000 \times 2{,}000) + (500 \times 2{,}000)}$$
$$= \frac{1{,}000{,}000{,}000}{3{,}500{,}000} = 285{\cdot}7 \text{ ohms.}$$

In the process of electrical testing it is frequently found to be necessary to employ wires of various resistances, either as standards for comparison, or simply for the purpose of placing in a circuit and varying the strength of the current therein. The wires are usually coiled up or wound on bobbins, so as to occupy little space, and are then placed in a convenient case or box; such a set of coils is known as a resistance-box, or rheostat. But if the coils are to be of any real value as standards, great care must be exercised, not only in accurately measuring their resistance, but also in selecting the materials of which they are made, so as to avoid deterioration or change of any kind. The wire must be completely covered throughout by some good insulating substance, to prevent contact between adjacent convolutions, and the material used for this purpose must be able to withstand without change the highest temperature to which it is likely to be subjected; and it must also be incapable of producing any injurious action on the wire. The best insulating material is silk thread, which is wound spirally over the wire in one or two layers.

In selecting the material for the wire itself, several points should be carefully attended to. The metal must be free from any liability to alteration by oxidation, &c. (iron is, therefore, unsuitable). But the most important matter for consideration is the amount of its variation in resistance, with a given change of temperature.

In very important work it is necessary to know the temperature at which a coil was originally measured, and either bring it to that same temperature during the experiment or else make a correction in the result. But either course is somewhat tedious, and in ordinary cases impracticable. In practice the coils are measured at the temperature at which it is probable they will generally be used, say 15° C. (59° F.), and the error lessened by choosing a metal whose percentage of resistance variation with change of temperature is very low.

In addition to changing with any alteration in the temperature of the atmosphere, the wire is more or less heated by the passage of a current itself, so that its resistance may easily alter during a brief or rapidly-performed test or experiment. An examination of the table given on page 19 shows the variation of a platinum silver alloy to be very small, and it is therefore very extensively employed in high-class apparatus, where the expense becomes a matter of minor importance.

For coils of high resistance it is necessary to choose a metal whose specific resistance is high; otherwise the length of wire would probably be inconveniently great. For low resistances, however, this is not so important; in fact, if a metal of high specific resistance is then used, the wire must be comparatively thick, otherwise it would be so short that very great difficulty would be experienced in making the coils of exactly the right resistance, because a considerable difference would be caused by a small error in the length of the wire. In all cases, however, there is the great advantage in the case of a thick wire, that a given amount of heat raises its temperature to a less extent than it would a thinner wire.

Copper is very unsuitable for resistance coils on account of its great variation in resistance, and, as its specific resistance is low, it would be necessary to employ either a very long or a very fine wire to make a coil of high resistance.

Taking into consideration cost, durability, high specific resistance, and low temperature error, German silver is undoubtedly the most useful material for the purpose; and it is consequently used more frequently than anything else.

A single resistance coil—such, for example, as a standard coil, or one designed for some other special purpose—is, after having been carefully wound on an ebonite or boxwood bobbin, usually mounted in a wooden case or box, furnished with an ebonite cover. Two brass blocks or plates, to which the ends of the wire are soldered, are screwed on to the under side of this cover. Connection with the external circuit is made by means of terminals fixed on the top of the case, and connected electrically with the plates underneath. The form of terminal employed is a matter of more importance than it is usually considered to be, for the contact surfaces at the junction of two conductors, or two parts of the same conductor, always offer some resistance, and if these surfaces are oxidised or dirty, or if the contact is not firm, this resistance will probably be considerable. It is for this reason that the form of terminal or binding-screw shown in fig. 3 is open to serious objection, the contact being as a rule uncertain. Such terminals, in which dependence for good contact has really to be made upon the end of a screw (frequently pointed as if to accentuate the evil), should be eschewed, at least for small wires or such as can be readily bent with the fingers. A much better and more reliable terminal is that shown in fig. 4, where the wire is clamped between a fixed base and a screw nut. In tightening the nut, a rubbing effect is produced, which assists in removing any superficial dirt either on the wire or on the terminal, and so tends to ensure good and steady contact. When using this terminal the wire should be bent round the screw shaft, otherwise there will, in tightening up, be a risk of bending the shaft. With the large wires used in electric lighting it is inconvenient and sometimes impracticable to bend the wire. In that case the first-mentioned type of terminal, fig. 3, or a modification of it, is resorted to.

FIG. 3.

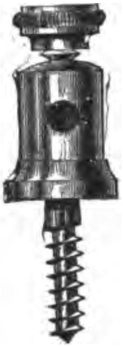
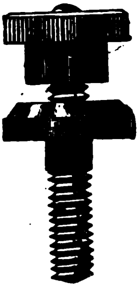
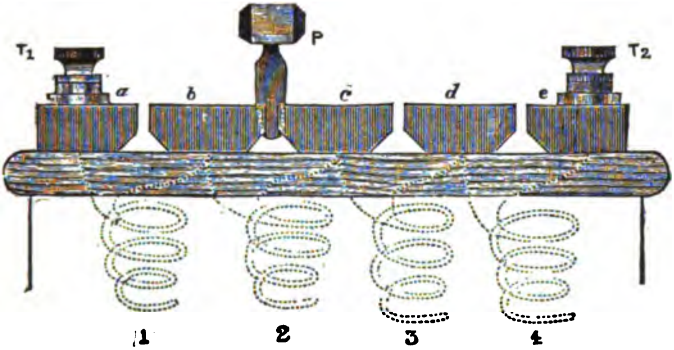


FIG. 4.



As it more generally happens that a number of coils are required to be so put together that the resistance to be introduced into any particular circuit can be varied at will from the zero to the maximum, special devices have to be employed to obtain this result with the smallest possible waste of time. Fig. 5 shows the best method of casing a number of coils of various resistances; all the coils are joined in series, and the junction of each pair is soldered to the bottom of a brass block, as shown in the figure, great care being taken in winding to ensure the absence of contact or leakage between one portion of the wire and another. The bobbins are fixed to the under side of the ebonite top of the case, the wires being connected to the brass blocks *a*, *b*, *c*, *d*, *e*, which are firmly fixed to the upper side of the ebonite, the adjacent ends of the various blocks being turned out to receive a slightly tapered or conical brass plug. The end blocks are fitted with terminal screws, T_1 and T_2, to which any extraneous wires can be connected. Now, if a wire leading from the copper pole of a battery is joined to a terminal, T_1, and another from the zinc pole to T_2, a current will flow through the resistance box, starting from the left-hand block *a* and passing through the resistance coil No. 1 to the second brass block *b*. Here it has two paths open to it; one through the coil No. 2, of comparatively high resistance, the other through the brass plug P, which has, practically, no resistance at all. All the current will therefore pass by the latter path, and none through the coil, which is said under these circumstances to be 'short-circuited' by the plug P. The

FIG. 5.



current must pass through the coils 3 and 4 before it reaches the terminal r_2.

The brass plug, which should be furnished with an ebonite cap or top, must be carefully tapered to fit the hole *exactly*. Should there be the slightest shake, or should there be any dirt or grit on the blocks or on the plug itself, the contact will be uncertain and the resistance variable. When properly made, the plug, on being inserted with some pressure and a slight twist—say to the right—should fit so thoroughly that on raising it the resistance box should be lifted with it. To remove the plug it should be necessary to first loosen it by giving a slight twist to the left. The lower and the two vertical edges or corners of the blocks should also be filed away to give a larger ebonite insulating surface between the blocks and to allow this surface to be kept clean. This arrangement is necessary in order to prevent, as far as possible, any short-circuit being caused by the accumulation of dust and dirt.

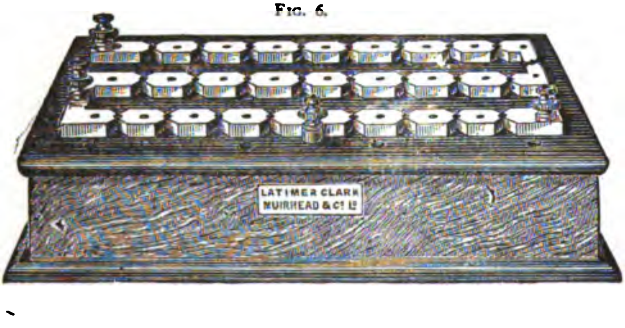
Resistance coils fitted in this way can easily be put in or taken out of the circuit, by withdrawing or inserting plugs between the brass blocks to which the ends of the various coils are soldered. It is hardly necessary to remark that the surfaces of contact should not be lacquered, but should be kept bright and clean.

Resistance coils are frequently used in conjunction with and in the immediate vicinity of delicate measuring apparatus in which a sensitive magnetised needle is employed. If, in such cases, the coils are wound continuously on the bobbin, or in the same manner as a solenoid, an electro-magnetic field of force will be set up immediately a current is sent through the coils, which may be sufficiently strong to impart motion to the needle. If the instrument is being employed to measure the current passing through the resistance, or any effect of that current, serious errors may therefore be introduced by the direct effect of the coils upon the needle. Again, as we shall see later on, it is impossible to start or stop a current in a solenoid suddenly, because work is done and time occupied in establishing, and again in disestablishing, the electro-magnetic field. These are serious defects, and it is fortunate, therefore, that the remedy is simple.

To obviate the difficulty it is only necessary that the wire should be wound 'double'—that is to say, the required length should be measured off and then doubled in the middle, the two halves being wound on together. The meaning of this will perhaps be more apparent on referring to the illustration (fig. 5). The double winding is more easily managed, especially with long coils, by winding the two halves off two separate spools or bobbins and soldering the inner ends together. In either case the two extremities of each coil are brought out together. We have thus two similar helices or solenoids carrying currents equal in strength but opposite in direction. The consequence is that the disturbing effect which would be produced by one solenoid is counteracted or neutralised by the opposite effect which would be due to the other.

When the coils to be enclosed in a box are numerous, it is inconvenient to place them in one long row and thus make a long narrow box. It is preferable to arrange them in two, three, or more parallel rows, connecting these rows together by brass blocks and plugs, as indicated in fig. 6. The centre of each block should also be provided with a tapered hole of the same size as those between the blocks, in order that the plugs may be placed in them when not in use for short-circuiting the coils. It is most important that all the holes and all the plugs should be of exactly the same dimensions, so that the plugs may be interchangeable, or that any one plug may be used for any of the holes. Failing this, considerable inconvenience and risk of error would speedily ensue, for then there would be a particular plug for each hole,

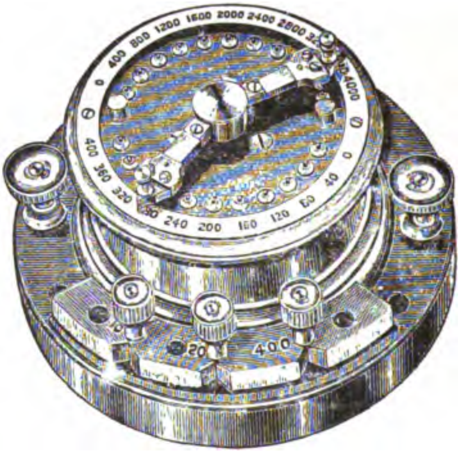
FIG. 6.



and very great difficulty would be experienced in using them and keeping them in their proper places.

Another very useful form of resistance-box or rheostat is shown in fig. 7. The coils are placed inside a round brass case

FIG. 7.



or box provided with an ebonite top and mounted on a mahogany base. Ten coils, each of 40 ohms resistance, are connected to eleven rounded steel points projecting through the ebonite top of the instrument. Ten other coils, each of 400 ohms resistance, are connected to the steel points on the other half of the top side of the ebonite. A number of other coils are connected to the brass blocks fixed on the base of the instrument and resembling those already described; when not required these latter are short-circuited by the usual brass plugs. Supposing the current to enter by the right-hand terminal, it will pass to the nearest brass block, then through the coils of 400,[1] 20, and 10 ohms (or through such plugs as may be inserted between the respective blocks), to the brass block nearest to the left-hand terminal. It then passes by a piece of insulated wire under or in the base of the instrument to the zero stud on the right-hand side, whence it will pass through the 40-ohm coils until it reaches the steel spring carried by the front brass arm, which is movable over these coils and studs. Passing along this arm, which is metallic throughout, it will enter the other movable arm and thence pass to the 400-ohm coils. Leaving at the zero-stud of these 400-ohm coils on the left-hand side, it will pass by a thick wire direct to the left-hand terminal and so to the other part of the circuit. The two arms can be readily moved round over the steel studs or points, so that the range of one arm is from 0 to 400 ohms, and that of the other from 0 to 4,000 ohms. The total resistance in circuit with the arms as shown, and all three plugs *in*, is 3,880 ohms. Although it is a great advantage that the resistance can be very readily varied, the instrument is somewhat objectionable for delicate measuring purposes, as the springs are apt to get weak and the contact unreliable, the resistance then becoming variable.

---

[1] This coil is usually made of 4,000 ohms resistance.

Another method of casing and joining up resistance coils is shown in figs. 8 and 9. A (fig. 8) is a circular brass plate; *b*, *c*, *d* are brass blocks. A tapered hole is provided between each of these outer plates and the plate A for the usual conical plug. T_1 T_2 are the terminal screws, the latter of which is permanently connected to the brass plate A. One end of each of the three coils is soldered to terminal T_1, and the other end of each to one or other of the outer brass blocks. When it is desired to *insert* in the circuit one of the resistance coils, the plug is placed in the

FIG. 8.

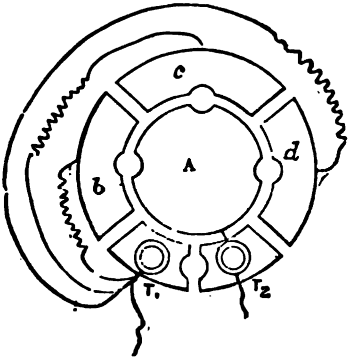
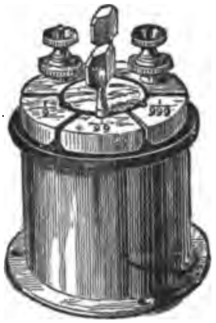


FIG. 9.



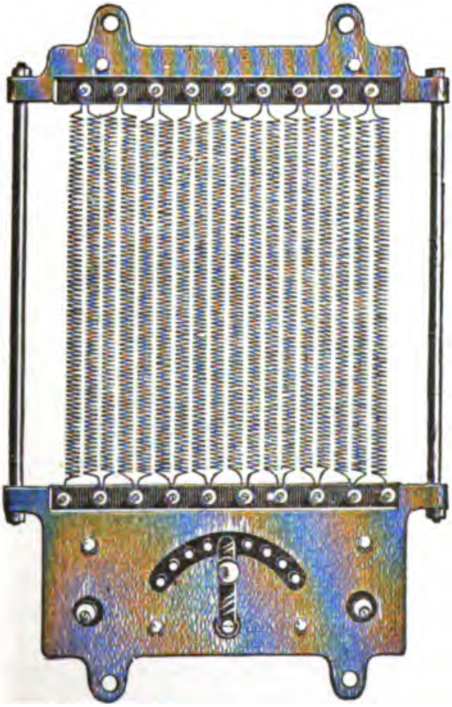
hole which is between the block connected to that coil and the plate A.

Thus the action is the reverse of that described in the last method, for here we insert a plug to insert resistance, removing it to cut out the resistance. Only one coil can, however, be used at a time; and if the plug is placed between terminals T_1 and T_2 the whole box is short-circuited. Fig. 9 shows a box of coils connected according to this method. It is designed for use with a galvanometer as a set of 'shunt coils,' having respectively $\frac{1}{9}$, $\frac{1}{99}$, and $\frac{1}{999}$ of the resistance of the galvanometer. (The nature and applicability of shunt coils will be dealt with in Chapter IV.)

For general use as well as for accurate measurements, the form of resistance-box shown in figs. 5 and 6 should be used. But where a means of rapidly varying the resistance is necessary, the form shown in fig. 7 is often employed. As we have already remarked, resistance varies considerably with temperature, whence every set of coils should have marked on the case the temperature at which they were measured. Then for very accurate tests they may either be brought to that temperature or a correction made in the reading, but in any case it is known whether any great error is likely to be caused by using them at any particular temperature.

It sometimes happens, however, that sets of resistance coils are required merely for the purpose of dissipating a certain amount of electrical energy. For instance, it becomes necessary, when employing some dynamo-electric machines, to reduce the electrical output in response to a correspondingly reduced demand made upon it by the external circuit; and this can be done by joining extra resistance in series with the magnet coils, and allowing some of the power to be expended in heating this extra resistance. In such cases it is not necessary to know exactly the value of the resistance in ohms, but it must be divided into a number of approximately uniform sections, so that its value can be changed gradually. As the currents employed are, in such cases, very powerful, it is important that the coils should be able to withstand a considerable rise in temperature without being in any way injured. The wire must therefore be left bare, so that the heat generated can be dissipated by radiation and convection. Were the wire to be covered with any insulating material, the dissipation by both these processes would be impeded, and there would be the further disadvantage that this sheathing would be sooner or later damaged, if not destroyed. The wire should be of a metal which has a fairly high specific resistance and fusing point, and should not be liable to deterioration by combining with atmospheric oxygen. For these reasons, German silver and tinned or galvanised iron are usually employed, but in special cases platinoid is resorted to. It is essential to select for the supporting frame a material which, while strong, is also non-inflammable and a good insulator, with the smallest possible power of condensing atmospheric moisture upon its surface. In fig. 10 is shown such a set of resistances, constructed by Messrs. Goolden & Co., and

FIG. 10.



suitable for carrying very heavy currents. There are two cast-iron end frames, which are hollow and have slate slabs fitted into them, these slabs being held in position by bolts which pass through both the slate and iron frame. The slabs, projecting inwards from the frames, carry a series of brass bolts and nuts, on to which are fixed the ends of spirals of bare German-silver wire. Slate is an effective insulator for the purpose, and the device of passing the connecting bolts right through it and securing them with nuts, instead of trusting to a screw-thread cut in the material, renders it mechanically satisfactory. The frame is completed and made rigid by a pair of iron rods which are secured to the cast-iron ends. The whole of the spirals are joined in series, the terminals for connection to the external circuit being fixed on to the slate through holes in the bottom end-frame. The left-hand terminal is joined to the bottom of the left-hand spiral, while the right-hand terminal is connected to the lever of a switch which passes over nine contact pillars rising from the slate bed through an opening in the frame. These pillars are connected to the lower junctions of the spirals, and by altering the position of the switch the spirals can be cut in or out of circuit, in pairs, as desired. The iron frames are 12 inches in width, the length being varied up to about 2 feet 6 inches by the employment of connecting rods of different lengths. A set of resistances similar to that illustrated is capable of dissipating about 1,000 watts without undue heating.

We have seen that whenever a current of electricity flows, a certain amount of energy is expended; and it is necessary to be able to measure exactly, the amount of energy so expended in any circuit or in any part thereof. The quantity of work performed in raising a mass of one pound through a difference of level of one foot against the force of gravity, is generally taken as the unit of mechanical energy and is known as the foot-pound. The work done in raising any mass through any height, is found by simply multiplying together the number of pounds in that mass by the number of feet through which it is lifted. Somewhat similarly we can take as the practical unit of electrical energy, the amount expended in transferring a unit quantity of electricity (one coulomb) through a difference of potential of one volt. And by multiplying the number of coulombs which have flowed from one point to another by the difference of potential in volts between those points, we obtain the number of units of electrical energy expended during the passage of the current. The unit of electrical energy, or one coulomb multiplied by one volt, is called the joule. As a simple numerical example we may suppose a current of 10 amperes to flow for 5 seconds, then the quantity of electricity passing through the circuit would be 50 coulombs, and if this current were maintained by a potential difference of 8 volts, the amount of energy expended in that time would be 8 × 50 = 400 joules.

As a rule we wish to know the *rate* at which work is being done in any circuit, rather than the amount which is done in a given time. It is evident that this rate can always be found by dividing the amount of work by the number of seconds taken for its performance, but the same result can be arrived at by multiplying together the potential difference and the rate of transference or flow of electricity. instead of the quantity actually transferred in a given time. Now the rate of flow of electricity is what we know as the current strength, which is measured in amperes. Therefore, if the difference of potential in volts between any two points is multiplied by the resulting current in amperes, the product gives the rate at which energy is being expended, or the rate of working between those two points. The unit rate of working or the unit of *power* is called the *watt*—that is to say, 1 ampere × 1 volt = 1 watt. Therefore, if a difference of potential of 20 volts between the ends of a wire maintains a current of 3 amperes, the rate of working is 3 × 20 = 60 watts.

It is desirable that the relation between mechanical and electrical rates of working should be understood. The mechanical unit is termed the 'horse-power,' and is equal to that rate of working which, if continued for one minute, would expend 33,000 foot-pounds of energy, or raise 33,000 pounds one foot in height. One horse-power is equal to 746 watts, so that, having calculated the number of watts absorbed in any particular case, on dividing this number by 746 we get the rate of working, or rate of loss of energy, expressed in horse-power. This power of 746 watts is, therefore, frequently referred to as the electrical horse-power.

Subsequent to the passing by Parliament of the Bill making the Board of Trade the arbiters of the destinies of electric lighting concerns, the Board selected a larger practical unit of electrical power. It is known as the Board of Trade unit, and is equal to 1,000 watts, or the power expended by 1,000 amperes at a potential difference of 1 volt. A convenient name for this unit is the kilowatt.

The units described in this chapter are those which are, and which will continue to be, employed in practice by the electric lighting engineer. No effort should therefore be spared to master the simple relation existing between the ampere, volt, ohm, horse-power, &c.

But it is advisable to know the method by which the various electrical units have been evolved, for they have not been selected arbitrarily, like the pound, yard, and gallon, but are built up on the fundamental conceptions of length, time, and quantity of matter, and are inseparably linked together. Perhaps the simplest measurable quantity which we can conceive is that of length, and in deciding upon a unit of length an effort was made to select some unalterable natural distance. The length of an earth quadrant—that is, the distance from the equator to the pole along a meridian—was agreed upon, and one ten-millionth part of this taken as the practical standard of length, and called a metre. The original measurement of the earth quadrant proved to be considerably in error, and consequently the simple relation between it and the metre was upset. But the metre thus determined is retained as the standard of length, and one hundredth part of this length, called one centimetre, is taken as the basis of the units upon which the system now to be briefly described has been reared. A square centimetre is the area contained in a square each of whose sides is one centimetre, and a cubic centimetre is the volume contained in a cube each of whose edges is one centimetre in length.

The next unit required is that of mass, or quantity of matter, and it should be remembered that the force of gravity acts upon every body in exact proportion to its mass, or the quantity of matter in it, independently of its size; therefore, what we know as the weight of any substance is exactly proportional to its mass. The unit of mass is called the gramme. It is equal to the mass contained in a cubic centimetre of pure water at its maximum density, i.e. at 4° Centigrade.

The third unit, that of time, is called the second. It is the length of time known in England by that name, and is the 86,400th part of a mean solar day.

The great value of a system built upon such units as those described is that it is always possible to recover any one of them, and so reconstruct or verify the system if necessary, although the process is no doubt difficult and tedious. The term 'absolute' has been applied to such a system, but it is not easy to see the precise application of the word here. It is usual, and certainly far better, to refer to it as the centimetre-gramme-second, or the C.G.S., system.

The next conception in order of simplicity, is that of the rate at which a mass of matter changes its relative position, or the velocity with which it moves. Velocity is estimated by dividing the distance in centimetres through which a body moves by the time in seconds taken to travel that distance. The unit is a velocity of one centimetre per second.

A mass of matter cannot, by any property belonging to it, change its position or its state of rest or motion, by itself. That which is competent to move, stop, or vary the motion of a mass of matter is called force, and the greater the force, and the longer the time during which it acts, the greater will be the increase or decrease in the velocity of a given mass. The unit of force is called the dyne; one dyne is that force which, by acting upon a mass of one gramme during one second, can impart to it a velocity of one centimetre per second.

When the position of a body is changed in opposition to any resisting force, work is done or energy expended, the amount being estimated by multiplying together the force overcome and the distance through which it is overcome. The unit of work is called the 'erg,' and is that work done when a force of one dyne is overcome through a distance of one centimetre; the energy expended is in every case equal to the work done, therefore the erg is also the unit of energy. We have seen that the practical unit of work, or expenditure of energy, is the joule: and one joule is equal to ten million ergs. Consequently, the practical unit of power, or rate of doing work, called the watt, is equivalent to ten million ergs per second.

Current strength is measured by the quantity of electricity which flows past any point in a circuit per second. The unit is that current strength which, when one centimetre of its path—that is to say, one centimetre of the conductor carrying the current—is curved into an arc of one centimetre radius, exerts a force of one dyne upon a unit magnet pole placed at its centre. The conditions of this unit will, however, be better understood after studying Chapter IV. The practical unit which is called the 'ampere' is equal to one-tenth of this so-called 'absolute' unit.

The unit quantity of electricity is that quantity conveyed by unit current in unit time. The practical unit, the coulomb, is therefore also one-tenth of the absolute unit.

The unit difference of potential between two points exists when one erg of work has to be performed in urging one unit of electricity against the electric force, or when one erg is expended by the flow of one unit of electricity from one point to the other. The volt or practical unit is 100,000,000 times the absolute unit.

Unit resistance exists when unit difference of potential causes unit current strength to flow through it. It follows, therefore, that the ohm is equal to 1,000,000,000 absolute units. The units which chiefly claim our attention are those of current, quantity, potential difference, and resistance. It is not possible to provide an invariable physical standard of either of these except resistance, which fact to a certain extent increases the importance attached to the unit of resistance. As has been pointed out, a reliable physical standard, in the form of a column of mercury of certain dimensions, has been selected to represent the ohm.

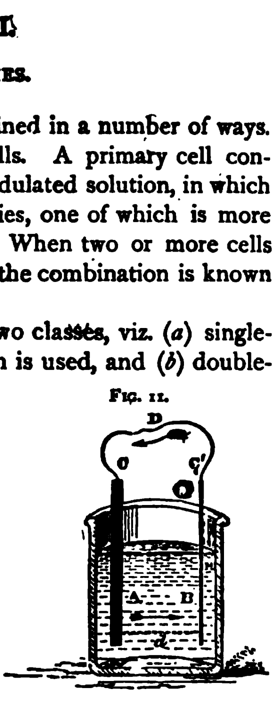
CHAPTER III.

PRIMARY BATTERIES.

A CURRENT of electricity can be maintained in a number of ways. One of these is by means of primary cells. A primary cell consists of a vessel containing a saline or acidulated solution, in which are immersed two solid conducting bodies, one of which is more assailable than the other by the liquid. When two or more cells are joined together to increase the effect, the combination is known as a battery.

Primary cells can be divided into two classes, viz. (*a*) single-fluid, or those in which only one solution is used, and (*b*) double-fluid, or those in which two solutions are employed.

FIG. 11.



The single-fluid cells are typified by the 'simple cell,' which was referred to on page 2, and which consists of a glass or earthenware vessel (fig. 11) nearly filled with water acidulated with a small proportion of, say, sulphuric acid, and containing a piece of zinc, A, and a piece of copper, B. On connecting the plates by a piece of wire, C' C, and thereby causing the current to flow, the surface of the zinc is attacked and sulphate of zinc is formed, hydrogen gas being liberated at the surface of the plate B.

This reaction may be represented by an equation, thus:–

$$\underset{\text{Zinc.}}{Zn} + \underset{\text{Sulphuric acid.}}{SO_4H_2} = \underset{\text{Sulphate of zinc.}}{SO_4Zn} + \underset{\text{Hydrogen.}}{H_2}$$

No chemical effect whatever is produced on the surface of the plate B, and it may here be noticed that the plate which is more or less dissolved, is called the positive plate, the other being called the negative plate. Chemical action may be supposed to take place throughout the entire length of the liquid or the distance between the plates, but it is not manifest except at the surfaces of the plates, and, for convenience' sake, it may be said to commence at the positive plate—that is to say, the acid particles, or, more correctly speaking, molecules* in contact with the zinc plate may be assumed to be the first decomposed, the hydrogen thus liberated attacking the next succeeding acid molecules in a similar manner. Hydrogen is again liberated, which again in its turn decomposes the adjacent acid molecules. A series of decompositions and recompositions is thus propagated throughout the entire liquid by a process of repetition, molecule for molecule, resulting finally in the deposition of the free hydrogen on the copper or negative plate. As the hydrogen thus deposited does not enter directly into chemical union with any of the simple metals, it remains in the gaseous state. The resultant changes present the appearance of the acid alone being affected, while the water remains constant and unchanged. The action may be expressed in chemical formulæ, thus :—

Before action.

$$\Big|\;\overline{\mathrm{SO_4H_2}}\;\overline{\mathrm{SO_4H_2}}\;\overline{\mathrm{SO_4H_2}}\;\overline{\mathrm{SO_4H_2}}\;\overline{\mathrm{SO_4H_2}}\;\Big|$$

Zinc or + **Copper or −**

In action.

$$\Big|\;\overline{\mathrm{SO_4}}\;\overline{\mathrm{H_2SO_4}}\;\overline{\mathrm{H_2SO_4}}\;\overline{\mathrm{H_2SO_4}}\;\overline{\mathrm{H_2SO_4}}\;\overline{\mathrm{H_2}}\;\Big|$$

Zinc or + **Copper or −**

The hydrogen is here released in a definite ratio to the amount of zinc dissolved. In fact, we may take it as an established law that the ratio between the weight of zinc dissolved and that of the hydrogen, &c., released by the passage of the current, is invariable, and that this ratio is dependent upon their respective electro-chemical equivalents.

We see by the above equation that for every atom or equivalent of zinc dissolved or converted into sulphate of zinc, two atoms of hydrogen are liberated. An atom may be defined as the smallest possible quantity of any substance capable of entering into or passing out of combination; and it will be seen, on referring to the accompanying table of atomic weights, or of the relative weights of individual atoms of some of the more important substances, that an atom of hydrogen weighs less than one of any other substance :—

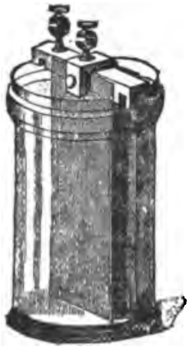
TABLE OF ATOMIC WEIGHTS AND EQUIVALENTS.

Elements	Symbol and Valency	Atomic Weight	Chemical Equivalent	Electro-chemical Equivalent (Milligrammes per Coulomb)
ELECTRO-POSITIVE.				
Hydrogen . . .	H^1	1·	1·	·010384
Potassium . . .	K^1	39·04	39·04	·40539
Sodium . . .	Na^1	22·99	22·99	·23873
Aluminium . . .	Al^3	27·3	9·1	·09449
Magnesium . .	Mg^2	23·94	11·97	·12430
Gold	Au^3	196·2	65·4	·67911
Silver	Ag^1	107·66	107·66	1·11800
Copper (Cupric) . .	Cu^2	63·	31·5	·32709
,, (Cuprous) .	Cu^1	63·	63·	·65419
Mercury (Mercuric) .	Hg^2	199·8	99·9	1·03740
,, (Mercurous) .	Hg^1	199·8	199·8	2·07470
Tin (Stannic) . .	Sn^4	117·8	29·45	·30581
,, (Stannous) . .	Sn^2	117·8	58·9	·61162
Iron (Ferric) . .	Fe^3	55·9	18·64	·19356
,, (Ferrous) . .	Fe^2	55·9	27·95	·29035
Nickel . . .	Ni^2	58·6	29·3	·30425
Zinc	Zn^2	65·	32·5	·33696
Lead	Pb^2	206·4	103·2	1·07160
ELECTRO-NEGATIVE.				
Oxygen . . .	O^2	15·96	7·98	·08286
Chlorine . . .	Cl^1	35·37	35·37	·36728
Iodine . . .	I^1	126·53	126·53	1·31390
Bromine . . .	Br^1	79·75	79·75	·82812
Nitrogen . . .	N^3	14·01	4·67	·04849

It is in consequence of this fact that hydrogen is taken as the standard in calculating the atomic weights of the various simple or elementary bodies. It will also be observed that an atom of zinc weighs sixty-five times as much as an atom of hydrogen. The meaning of the equation, therefore, is that for every sixty-five parts by weight of zinc dissolved, two parts by weight of hydrogen are liberated ; consequently, if we again regard the relative deposition of hydrogen as the standard, the weight of zinc dissolved will be 32·5 times as much, or, in other words, the electro-chemical equivalent of hydrogen being unity, that of zinc is 32·5. The equivalents of the other elementary bodies enumerated in the table have been calculated in a similar way.

The liberated hydrogen, in consequence of its low specific gravity, exhibits a tendency to rise through the water and escape into the air. Only a portion, however, of the gas escapes in this way, a large proportion adhering to the copper plate and forming, as it were, a gaseous film over the metallic surface. This accumulation, due to a variety of causes, is facilitated by the opposite polarities or electrical conditions of the copper and hydrogen which cause a mutual attraction to set in. There is a double effect of the accumulation which soon becomes apparent, for a gradual diminution in the current sets in, consequent first on the decrease in the copper surface exposed to the liquid (which involves a proportional increase in the internal resistance of the cell), and, secondly, on the tendency on the part of the positively electrified hydrogen film to set up a contrary current. Free hydrogen is, in fact, more positive than the zinc itself. When this condition is arrived at, the cell is said to be polarised. The effect of the passage of a current being, therefore, a reduction of the electro-motive force of the cell, such a combination is manifestly useless for purposes requiring a continuous and uniform current.

FIG. 12.



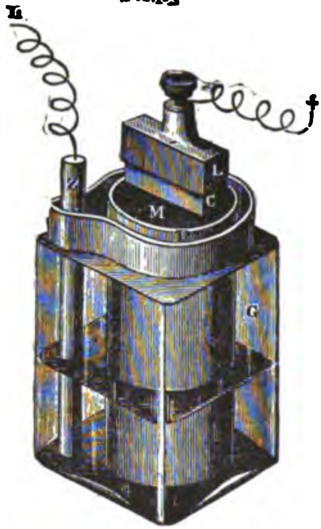
To overcome this really strong objection Smee constructed a cell (fig. 12), the peculiarity of which consisted in the nature of the surface of the negative plate. It had been ascertained that a smooth surface engenders a much more rapid accumulation of hydrogen than does a roughened surface. Accordingly, he used for his negative plate a thin sheet of silver covered with platinum in a state of very fine division, so that an irregular surface was produced. So treated the plate is known as platinised silver. There are two zinc plates connected to the same terminal, but placed one on each side of the silver, the solution being 1 of acid to 10 of water. This cell, which is still largely used, is considerably more lasting than the simple cell ; the unevenness of the negative surface facilitates the ascension of the hydrogen particles more nearly in proportion to the rate of production. It has also a higher electro-motive force because of the substitution for copper of a more electro-negative plate. This form of battery is useful where currents are required for brief periods, but it is far from being a constant cell, that is, one which yields a *continuous and uniform* current. When, however, the cell is put together of abnormally large proportions, it approximates more nearly to the condition of a constant cell, and is used as such by many electroplaters.

The Smee cell is capable of being manufactured in a very compact form. The silver foil is fixed in a frame made by fastening together four pieces of wood about half an inch square in section, the upper edge of the foil being connected to a brass terminal on the top of the frame. The plates of zinc, a trifle larger than the foil, are placed against the two sides of the frame and all three are then clamped together by a strong brass terminal or clamp which is placed in contact with the zincs. The advantage gained by this form of construction is that the internal resistance of the cell is very low; first, because the two zinc plates are opposite to the two sides of the foil, and, secondly, because the distance between the foil and the zincs is very small. The wooden frame is necessary, to support the thin silver foil and to prevent it touching either of the zinc plates. Were there any other simple means of preventing this contact, the frame might be dispensed with.

There is in use at the Royal Observatory at Greenwich a remarkably simple and useful modification of the Smee cell. It consists of a plate of zinc and a plate of good gas-retort carbon, the upper portion of which is rendered non-porous by immersion in hot paraffin wax. The solution is one of dilute sulphuric acid, the acid being, however, very pure. The hydrogen bubbles can be seen rising freely through the solution, instead of adhering to the uneven surface of the carbon. The resistance of the cell is very low, and its electro-motive force, after a few minutes, remains steady at about half a volt.

A far more important cell than the Smee is the Leclanché (fig. 13), in which a zinc rod, Z, is used as the positive plate, while the negative plate C takes the form of a rod or slab of gas carbon, or of prepared carbon. The gas carbon is one of the by-products in the manufacture of gas, and is formed by the condensation of a portion of the carbon in the cooler portions of the retort. The prepared carbon is made by subjecting to considerable pressure, at a high temperature, a mixture of powdered carbon and some treacly substance which is employed for cementing the carbon particles. The carbon plate is placed inside a vessel of porous (unglazed) earthenware, which is then filled with a mixture of crushed, but not powdered, carbon and black oxide of manganese. The latter should be of the 'needle' or granular form, care being taken to exclude powder or dust. The outer vessel, G, is generally of glass, which enables the condition of the cell to be observed without removing any of the parts. The liquid consists of a saturated solution of sal-ammoniac, or chloride of ammonium, the porosity of the inner jar allowing the solution to diffuse itself somewhat freely, and so to moisten the mixture of carbon and black oxide.

FIG. 13



The zinc combines with the chlorine of the sal-ammoniac, forming zinc chloride, simultaneously releasing hydrogen and ammonia, which latter dissolves in the water until a saturated solution is obtained—that is to say, until the solution holds as much as it can support—after which it escapes as a gas readily recognised by its characteristic odour. It may, however, be remarked that water is not saturated with ammonia until it has absorbed 727 times its volume of the gas at a temperature of 15·5° C. or 60° F. The hydrogen, so far, remains free, as shown by the equation :—

$$\underset{\text{Zinc.}}{Zn} + \underset{\text{Sal-ammoniac.}}{2NH_4Cl} = \underset{\text{Zinc chloride.}}{ZnCl_2} + \underset{\text{Ammonia.}}{2NH_3} + \underset{\text{Hydrogen.}}{H_2}$$

It is, however, ultimately released inside the inner vessel, and there it deprives the manganic oxide of some of its oxygen, forming water and sesqui-oxide of manganese, thus :—

$$\underset{\text{Hydrogen.}}{H_2} + \underset{\substack{\text{Manganic}\\\text{oxide.}}}{2MnO_2} = \underset{\text{Water.}}{OH_2} + \underset{\substack{\text{Sesqui-oxide of}\\\text{manganese.}}}{Mn_2O_3}$$

The entire action may be represented by a single equation, thus :—

$$Zn + 2NH_4Cl + 2MnO_2 = ZnCl_2 + 2NH_3 + OH_2 + Mn_2O_3.$$

The action so represented is, of course, similar to that of the simple cell or the Smee, in so far as concerns the propagation of the series of decompositions and recompositions. There is, however, a subsequent or secondary reaction between the zinc chloride and the other constituents of the solution, resulting in the formation of what are called double salts, which tend to impede the efficient working of the cell.

One great advantage this battery has over most, if not all other forms, is that it does not in any way deteriorate by inactivity, unless the evaporation of the water can be regarded in this light, but even that may be prevented. It is no unusual experience for these cells to remain in work for upwards of a year without the necessity for any attention whatever, and even then it is probable that a jug of water is all that is required. It will be seen, from a study of the equations given above, that the working of the battery results in the gradual absorption of the zinc, and the decomposition of the sal-ammoniac, &c., which accordingly require replenishing at times. A whitish-yellow turbidity in the solution indicates the presence of an excessive amount of zinc chloride in proportion to the amount of sal-ammoniac, which latter should then be increased, although it would be as well to remove a portion of the solution and then fill up with water before adding the sal-ammoniac.

Considerable care is taken in the construction of this cell. As both sal-ammoniac and ammonia are corrosive and attack copper, brass, &c., all the exposed metallic surfaces should be well served with gutta-percha, pitch, paraffin wax, or some other non-corrosive and impervious material.

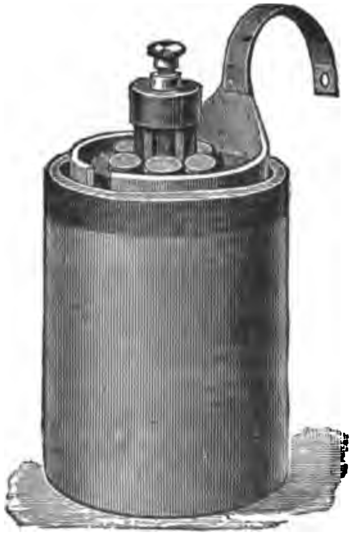
Where the batteries are made in very large quantities, it is the practice to drill two small holes through the upper extremities of the carbons, and, after raising these ends to a high temperature, to dip them into melted paraffin wax. They are subsequently placed into a mould containing molten lead, a terminal or binding-screw being cast into this leaden cap at the same time. The function of the wax is to close the pores in the upper portion of the carbon, and so to prevent the ammoniacal solution from creeping up to the terminal or leaden cap. Lead is interposed between the waxed carbon and the brass terminal because it is the least assailable of the ordinary metals. Pitch is run over the carbon-manganese mixture to keep the mixture and the carbon rod in position, and to form an impervious covering, holes being made in it, however, to permit any hydrogen or other gases that may be formed to escape. The upper parts of the porous pot, and the zinc rod and the connections, are likewise coated with pitch. Sometimes an india-rubber cover is made to fit over the top of the battery, so as to hold the porous pot and the zinc permanently in position, and to prevent the evaporation of the water.

The electro-motive force of this battery is nearly twice that of the Smee, while, owing to the large surface exposed, more particularly at the negative plate, the internal resistance is also low. The cell is, however, only useful for sending occasional or intermittent currents, such as are required in electric-bell work. In fact, the chief objection to this battery is the great rapidity with which it polarises and so becomes temporarily useless, owing probably to the fact that hydrogen is liberated faster than the manganic oxide can be decomposed. Consequently, a more or less perfect film of hydrogen is deposited over the surface of the carbon. That this is the case is in a measure demonstrated by the fact that if the cell is allowed to stand idle for a brief interval of time it will again yield its full current. This intermittent action obviously limits very materially the cell's sphere of usefulness. The defect, although very marked when the resistance of the circuit is very low, is reduced to a minimum when the resistance is high, because the current is then feeble and the chemical reactions proportionately less. The fact that the constituents of the cell remain inactive when the cell is idle, is a point of very considerable importance, and is a very useful feature, for it means that there is no wasteful action in the battery, such as we shall find there is in practically every other type of battery—at least, in every battery in which an acid plays a part. Cleanliness is, however, absolutely necessary in dealing with the Leclanché, or, indeed, with any other form of battery, and it is essential that the containing vessel, whether of glass or earthenware, should be kept dry externally. The latter desideratum is usually accomplished by coating the upper portion of the outer surface of the vessel with pitch or some other such substance as will not permit the liquid to 'creep' over its surface, for the salt (sal-ammoniac) has a strong tendency to crystallise out. Should the solution be allowed to creep, we have to contend not only with the waste of salt so occasioned, but also with the 'leakage' of electricity that would take place over the moistened external surface.

There is a modification of the Leclanché which is of some importance and which is known as the 'agglomerate' Leclanché. The negative element consists of a carbon plate or block, having in contact with it blocks of agglomerated carbon and manganese. The latter are prepared by intimately mixing 40 parts of manganic oxide, 55 parts of gas carbon, and 5 parts of gum lac resin, and submitting the mixture, placed in a steel mould, to a temperature of 100° C., applying at the same time considerable hydraulic pressure. The result is a solid compact mass, and, as the chief function of the porous pot in the older type is to support the mixture of crushed carbon and manganic oxide, it is apparent that that vessel, which materially increases the internal resistance of the cell, can be dispensed with. India-rubber bands placed round the agglomerated blocks (which in their turn embrace the carbon block), keep the whole of the compound negative element together. In the earlier forms of agglomerate cell, rectangular blocks of agglomerated manganic oxide and carbon were held against the two faces of a flat plate or block of carbon, and the india-rubber bands holding the three blocks together were specially made so as to hold also the zinc rod, which was of the usual type.

But a much better form is that known as the 6-block agglomerate (see fig. 14), which is very extensively used. The negative element consists of a block of carbon with six fluted sides, which is capped with lead and fitted with a terminal after the top of it has been steeped in hot paraffin wax. In each of the sides is laid a round stick of the agglomerated carbon and manganic oxide, the whole being wrapped round with a piece of coarse canvas, and held in position by a couple of stout india-rubber bands. The canvas does not, of course, prevent intimate contact between the rods and the solution, nor does it appreciably increase the internal resistance of the cell, its function being simply to prevent pieces of the agglomerate rods falling out and 'short-circuiting' the cell, by joining the positive and negative elements together. Instead of employing a zinc rod for the positive element, a large piece of sheet zinc (about $\frac{1}{8}$ inch thick) is rolled into a cylinder, the approaching edges being, however, kept a quarter of an inch or so apart to allow of the free circulation of the solution. In consequence of the very large increase in the amount of surface thus exposed to the liquid, the internal resistance is very considerably reduced, polarisation being also to a great extent prevented or at least impeded. The current produced is much more uniform than that from the old type Leclanché. As a matter of fact, when employed upon circuits offering high resistance, an almost constant current is produced, and, as the cell is pre-eminently a clean one, as the cost of maintenance is very low, and as there is a total absence of wasteful action when the cell is idle, it is rapidly gaining ground and driving out of the market many other types of cell, such as the Daniell and the Bichromate (to be presently described). In fact, for ordinary work on circuits of high resistance, or even for hard but intermittent work on circuits of low resistance, we know of few, if any,

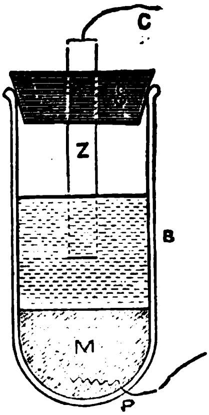
FIG. 14.



serious objections to its use, while, on the other hand, it possesses the important advantages above enumerated.

The 'Standard' cell (fig. 15), invented by Mr. Latimer Clark, is an important one. It is designed solely as a standard of electro-motive force, and is largely employed for purposes of measurement. It is made in a small glass vessel, such as a short wide test-tube, a layer of pure distilled mercury, M, being employed as the negative plate which covers the bottom of the glass vessel to a depth of half an inch or so. Over this is placed the 'liquid' or electrolyte, which consists of a thick paste, B, made by mixing mercurous sulphate with a saturated solution of zinc sulphate. The positive element is a rod of pure distilled zinc, Z, which dips into the paste. It is usual to seal the battery by means of paraffin wax or india-rubber, S. Connection is made with the zinc by means of a copper wire, C, soldered to the upper end of the zinc rod passing through the wax or rubber stopper. A platinum wire, P, fused into the bottom of the vessel, makes contact with the mercury.

FIG. 15.

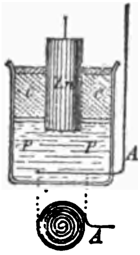


It is highly essential that the constituents of the cell should be absolutely pure, hence the necessity for re-distilling the zinc and mercury. The mercurous sulphate can be made by dissolving pure mercury, placed in excess, in hot pure sulphuric acid. The sulphate is an insoluble white powder, and should be well washed with distilled water before it is mixed with the zinc sulphate, to remove any trace of the mercuric sulphate or of free acid. The mercuric contains a larger proportion of mercury than the mercurous sulphate, and, on the addition of water, imparts to it a yellowish tinge.

The chemical action which takes place during the passage of a current is to decompose the mercurous sulphate, adding the mercury released to that already in the vessel, an equivalent of zinc being dissolved off the positive rod.

The electro-motive force of this cell is 1·435 volts and is exceedingly uniform, providing only a high external resistance, not less than 1,000 ohms, is employed. If the resistance of the circuit is low, the current becomes proportionally strong. The mercury salt is not then capable of being decomposed at a corresponding rate, whence polarisation sets in and the electro-motive force falls in consequence. The electro-motive force also decreases with an increase of temperature, the rate being about 0·08 per cent. per degree Centigrade.

FIG. 16.



The commercial form of Clark cell constructed after the plan of Dr. Muirhead is illustrated in fig. 16. Instead of using a layer of mercury, the platinum electrode A, fused through the glass-containing vessel, is made of a long piece of wire which is coiled into a close flat spiral and coated with mercury, either by heating and then immersing it in a mercury bath, or by heating the mercury and the platinum together. The spiral is then embedded in the paste, composed of pure mercurous sulphate and a saturated solution of pure zinc sulphate, *p*. The pure zinc rod, *z*, is dipped into the paste, and a cement stopper, *c*, holds the whole firmly together, so that the cell is made more portable than that shown in fig. 15, which has the disadvantage that the constituents of the cell are liable to become mixed if it is not used very carefully. The mercury deposited on the platinum spiral is sufficient to form the negative element or 'plate,' so that a layer of mercury is not really necessary.

FIG. 17.

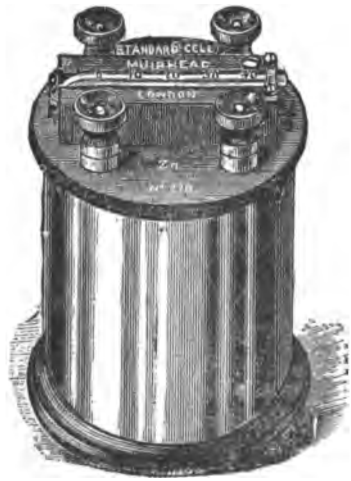
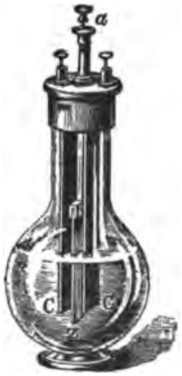


Fig. 17 shows the method employed for casing in. A cylindrical brass case with an ebonite cover is used, and contains two cells which can be balanced one against the other to test their relative electro-motive force, or they can be used together and give a double electro-motive force. A thermometer is likewise provided, the bulb being inside and the tube bent so as to lie over the scale on the cover. This is an important, though simple innovation, and assists in the avoidance of an error due to a varying temperature.

The only other form of single-fluid battery which we shall notice is that in which a solution of bichromate of potash is employed, and which is generally made in the form shown in the diagram (fig. 18). It consists of an alternation of zinc and carbon plates (always one more of carbon than of zinc), placed in a glass vessel containing the solution. The carbons are all connected with one terminal so as to give a large negative surface, and all the zincs with another to oppose a large positive surface to the solution. In most cases the zincs are attached to a metal rod, *a*, which slides in a hole in the cover, so that by raising the rod the plates can be readily removed from the liquid and the wasteful consumption of the zinc and bichromate of potash which would otherwise take place when the cell is idle prevented.

FIG. 18.



The solution consists of 1 part by weight of bichromate of potash, 2 parts of good sulphuric acid (of 1·8 specific gravity), and 12 parts of clean water. The bichromate of potash is first pulverised and then added slowly to the acid, stirring all the time. This converts the bichromate of potash into chromic anhydride and potassic sulphate, which precipitates in a beautiful crystalline formation, the chemical reactions being indicated by the equation :—

$$\underset{\substack{\text{Bichromate}\\\text{of potash.}}}{K_2Cr_2O_7} + \underset{\text{Sulphuric acid.}}{7SO_4H_2} = \underset{\substack{\text{Chromic}\\\text{anhydride.}}}{2CrO_3} + \underset{\substack{\text{Potassic}\\\text{sulphate.}}}{K_2SO_4} + \underset{\text{Water.}}{OH_2} + \underset{\text{Sulphuric acid.}}{6SO_4H_2}$$

Water is then added slowly, when the crystals are dissolved and the chromic anhydride converted into chromic hydrate or acid (H_2CrO_4) by the absorption of water, a quantity of the water being taken up, with the usual result that follows the admixture of sulphuric acid and water—viz. the evolution of a considerable amount of heat. The energy with which the acid unites with the water is very great, and it is this that necessitates the slow addition of the latter. If poured on too abruptly there is considerable danger of the mixture being ejected from the vessel and scattered about the person or on anything that may be near. As the acid is exceedingly corrosive, it is impossible to take too much precaution when adding the water. In ordinary cases where the acid and water are to be mixed it is by far the safer plan to add the acid to the water, as the former will then find plenty of the latter to satisfy its almost insatiable thirst.

When the solution of the crystals is completed and when the liquid has cooled down to the ordinary temperature, it is ready for use. On completing the circuit and allowing the current to flow, the zinc is dissolved, forming zinc sulphate, and the chromic acid is converted into chromic sulphate, water being liberated. The reaction may be expressed by the equation :—

$$\underset{\text{Zinc.}}{3Zn} + \underset{\text{Sulphuric acid.}}{6H_2SO_4} + \underset{\text{Chromic acid.}}{2H_2CrO_4} = \underset{\text{Zinc sulphate.}}{3ZnSO_4} + \underset{\text{Water.}}{8OH_2} + \underset{\text{Chromic sulphate.}}{Cr_23(SO_4)}$$

This battery has a high electro-motive force, while its resistance is very low. It yields, therefore, a considerable current, which does not, however, last long, rarely more than an hour or so, because of the rapidity with which the cell becomes polarised. On the other hand, when only used occasionally, the same solution will last for a very long time. As there is a tendency, by secondary chemical reactions taking place between the various constituents of the cell, to form hard crystals of a double salt (known as chrome alum) which at times cause a fracture of the jar, it is advisable to avoid square or flat cells for this battery. As we shall presently see, a modification is extensively used on account of its high electro-motive force, its low internal resistance, and its approximation to constancy.

We come now to consider the double-liquid batteries, the great aim of which is to obtain constancy, even if at the loss of a little power. The chief obstacle to constancy, we have seen, is the accumulation of hydrogen on the negative surface, which hydrogen must therefore be absorbed. Daniell, in 1836, was the first to achieve this object, which he did by using a metallic salt in the neighbourhood of the negative plate, separated from the zinc and acid solution by means of a porous division which, on being moistened, allowed the current to pass through it, but which at the same time prevented, or rather impeded, the intermingling of the two solutions. The conception of a porous division was certainly a brilliant idea, but so also was that which determined the kind of solution which was to surround the negative plate. This liquid contains a large quantity of the very same metal as that of which the plate itself is constructed, and it is due in a great measure to this fact that the Daniell cell stands alone, and pre-eminently so, as *the* constant cell. The cell is put together in a great variety of shapes and patterns, varying with the purpose to which it is intended to be applied. It consists essentially of an outer porcelain or other non-porous vessel, containing the zinc. Inside this is placed an unglazed earthenware vessel, which contains a piece of thin sheet copper. The porous vessel is nearly filled with copper sulphate (known more generally as bluestone), and water is poured on till the level is about the same as that in the outer vessel, which contains a solution of one part sulphuric acid, or zinc sulphate, with 12 to 20 parts of water.

The chemical reactions which take place in the Daniell cell are of a very simple character. On completing the circuit the zinc enters into action with the sulphuric acid and forms sulphate of zinc ($ZnSO_4$), releasing free hydrogen (H_2), in precisely the same way as in the simple cell. This hydrogen is not, however, liberated on the surface of the negative or copper plate, but at or near the porous partition where the two liquids meet. The hydrogen coming into the presence of the copper sulphate solution, proceeds at once to displace the metal from its combination, setting it free as metallic copper, and taking its place to form a new equivalent of sulphuric acid. The liberated copper acts in a manner very much akin to that of the free hydrogen in the acid solution—that is, it breaks up the next molecule of copper sulphate, and produces a new molecule of the same compound by replacement, and so on until the surface of the negative plate is ultimately reached, on which is deposited the finally released copper particle.

A little reflection will reveal to the student something of the greatness of the advance thus made by Daniell. In the first place, we find the released hydrogen, which was the great drawback in the simple cell, taken up entirely by a very easily decomposable salt, and thus prevented from polarising the battery. Furthermore, instead of the deposition of the foreign hydrogen film on the copper plate, copper purer than can be obtained by any other simple process is deposited. In fact, a similar process is employed commercially for the extraction of copper from its ores, and for the refinement of comparatively impure bars. The action that takes place from the zinc to the copper surface may be expressed thus :—

$$\underset{\text{Zinc.}}{Zn} + \underset{\substack{\text{Sulphuric}\\\text{acid.}}}{SO_4H_2} + \underset{\substack{\text{Copper}\\\text{sulphate.}}}{SO_4Cu} = \underset{\substack{\text{Zinc}\\\text{sulphate.}}}{ZnSo_4} + \underset{\substack{\text{Sulphuric}\\\text{acid.}}}{SO_4H_2} + \underset{\text{Copper.}}{Cu}$$

Or showing the effect on a few of the intermediate molecules :—

Before action.

$$\underset{\text{Zinc.}}{\lceil}\overline{SO_4H_2}\ \ SO_4H_2\ \ SO_4H_2 \underset{\substack{\text{Porous}\\\text{partition.}}}{\mid} SO_4Cu\ \ SO\overline{_4Cu}\ \ SO_4C\overline{u} \underset{\text{Copper.}}{\mid}$$

In action.

$$\underset{\text{Zinc.}}{\mid} S\overline{O_4}\ \ \overline{H_2S}O_4\ \ \overline{H_2SO_4}\ \ \overline{H_2 \underset{\substack{\text{Porous}\\\text{partition.}}}{\mid} SO_4}\ \ \overline{CuSO_4}\ \ \overline{CuSO_4}\ \ \overline{Cu} \underset{\text{Copper.}}{\mid}$$

We see here that for every atom of zinc dissolved one atom of copper is deposited, and for every molecule of sulphuric acid decomposed by the zinc, or for every molecule of cupric sulphate decomposed by the nascent hydrogen, one molecule of sulphuric acid is formed. Theoretically, then, the gross quantity of sulphuric acid should remain constant, zinc sulphate should be continuously increasing, while the sulphate of copper should diminish in precisely the same ratio—that is, one molecule or equivalent of zinc sulphate should be formed for every molecule or equivalent of cupric sulphate that is decomposed. Further, for every 65 parts by weight of zinc dissolved, 63 parts by weight of copper should be deposited.

A weak solution of zinc sulphate is frequently substituted for the sulphuric acid solution. In that case no hydrogen at all is generated, so that polarisation from this cause is altogether impos sible. The series of chemical reactions presents the same general features. On joining up, the zinc sulphate attacks the metallic zinc, fresh particles or molecules of the salt are formed, and metallic zinc liberated in place of the hydrogen which is produced when sulphuric acid is employed. The liberated zinc decomposes the copper sulphate, forming more zinc sulphate and liberating the copper. Eventually, copper is deposited on the copper plate, the reactions being set forth in the equation :—

$$\underset{\text{Zinc.}}{\mathrm{Zn}} + \underset{\substack{\text{Zinc} \\ \text{sulphate.}}}{\mathrm{SO_4Zn}} + \underset{\substack{\text{Copper} \\ \text{sulphate.}}}{\mathrm{SO_4Cu}} = \underset{\substack{\text{Zinc} \\ \text{sulphate.}}}{\mathrm{2ZnSO_4}} + \underset{\text{Copper.}}{\mathrm{Cu.}}$$

The substitution of the zinc sulphate for the acid has also the effect of reducing the wasteful consumption of the zinc. Unless the cell is required for immediate use there is really no need to add even the zinc sulphate to the water, the reason for which will be seen presently.

The chemical changes, however, which are brought about in the Daniell by the propagation of the current, constitute only a portion, and that a by no means large one, of the total amount of chemical change that ensues on fitting up the cell. That very porosity of the unglazed earthenware partition, while it allows the two solutions to come into contact, also permits of their diffusion or gradual mixing. All liquids do not diffuse at a uniform rate, the rate of diffusion varying inversely as the square of their specific gravities. The immediate consequence of this is, that some of the copper sulphate solution passes through into the zinc division, where its copper is displaced by zinc, thereby converting the copper sulphate into zinc sulphate. The copper so displaced is deposited in a black spongy mass upon the surface of the zinc, or is precipitated to the bottom of the cell as battery 'mud.' All this means so much waste, for the zinc is dissolved and the copper sulphate decomposed, without the production of any available current of electricity. The deposit on the zinc plate converts the cell, in a great measure, into one with two copper surfaces.

When the battery is intended only for occasional use, or when the external circuit is of relatively high resistance, it is much preferable to use somewhat denser porous partitions, whereby the diffusion of the solutions is to some extent prevented, or at least hindered. The presence of denser porous partitions implies, of course, a proportional increase in the internal resistance of the battery. It may here be mentioned that white unglazed porcelain is harder and less porous than the red variety, and is therefore generally to be preferred.

Great care must also be taken that the various constituents of the cell are of the purest possible character, and all metallic joints must be electrically continuous. A small percentage of impurity in either of the solutions will have most deleterious effects. Three substances are required as pure as our knowledge can render them. The copper sulphate must, above all things, be pure, because of the weakness of the chemical affinity between sulphuric acid and copper. In the event of the salt not being so, the impurities will precipitate the copper and then small 'local actions' will be called into existence, much to the prejudice of the primary or main current. The impurity most common in copper sulphate is iron, which may be readily detected, for, as liquids are essentially diffusive, a small test-tube full will give the same quantitative as well as qualitative result, as any larger quantity. Acid solutions of copper are of a brilliant green hue, while the corresponding ammoniacal solutions, due to the free addition of ammonia solution, are deep blue in colour. If, therefore, we add an excess of ammonia to the acid solution (*i.e.* more than sufficient to neutralise the acid), the copper will be readily retained in the solution, but with the change of colour mentioned above. Iron, however, while it is soluble in acid, is precipitated by ammonia—that is to say, the ammonia will not allow the iron to remain in solution. Should there, therefore, be any iron in the acid solution, it will be precipitated as a dark powder on the addition of the alkaline ammonia. The sulphuric acid or sulphate of zinc, when used, must likewise be free from impurities, the chief of which is again iron. This metal in sulphuric acid gives it a yellowish tinge, even when in small quantities. Good acid should be as colourless as pure water, and when poured from one vessel to another should, if of the requisite strength and specific gravity, have the viscidity of oil. The porous partition, unless carefully made, is liable to contain small particles of cinder, &c., and these tend to decompose the cupric sulphate with a precipitation of the copper, which forms itself into nuggets in the pores of the earthenware and frequently chip or even completely fracture it.

The zinc should be pure, or as nearly so as it can be obtained. Chemically pure zinc, however, is manufactured with great difficulty, and is consequently very expensive. The presence of foreign matter is, nevertheless, a very great deterrent to the good working of the cell, for it must be remembered that the presence in a solution of two metals in contact or otherwise electrically connected, always results in the production of electrical currents. If, therefore, there are particles of foreign metals mixed up with the zinc, there necessarily occurs local currents which act disadvantageously in at least two ways—first by wasting the zinc, and secondly by weakening the main current. As zinc is positive to every available substance (the only metals positive to it being potassium and sodium, which, on account of their extreme affinity for water, are never employed for battery purposes), the admixture of particles, say, of iron, tin, or arsenic, causes small currents to travel from the zinc to these particles, and while the impurities remain to a great extent unaffected (because of their being the negative element), the zinc is constantly suffering a loss by consumption or conversion into a salt. These minute currents are furthermore produced on the surface of the zinc, and must, as already mentioned, interfere considerably with the production of the primary current. The difficulties arising from the presence of impurities are also increased if the zinc is imperfectly or improperly manufactured. The molecular arrangement (or the relative position of the molecules) must be homogeneous throughout the surfaces of each plate, otherwise currents will be set up between the softer and harder parts of the zinc—in a word, they possess opposite electrical properties, so that even if chemically pure zinc were procured, it would not follow as a matter of course that we should be secured against this source of wasteful local action. Concentrated sulphuric acid has, it may be mentioned, no effect on pure zinc provided it is properly annealed—that is to say, that the surfaces have been softened and made molecularly homogeneous. The acid can, therefore, furnish us with a tolerably reliable test for the degree of purity and equable texture possessed by the metal. So important, indeed, is this question of uniformity that a difference of temperature will frequently determine a difference of potential, and therefore cause a current to flow.

The effect both of the presence of any impurity and of unequal hardness can, however, be effectually overcome, at least for a time, by the process known as 'amalgamation.' This process consists in first thoroughly cleansing the surfaces of the metal by immersing it for a time in a dilute sulphuric or hydrochloric acid solution, and subsequently (but while still wet with the acid) coating the surfaces with mercury. This operation is generally recommended to be performed by rubbing the mercury on with a sponge or piece of cloth at the end of a stick; but this is a very irksome and tedious operation, more especially when the zincs are cylindrical, and it is quite as, if not more, efficacious to pour the mercury (which should afterwards be used for no other purpose) into a flat vessel and lay or roll the zincs in it. This may be thought a wasteful process, but the superabundant mercury can be easily removed by wiping the surfaces over and then standing them on a dish, to allow any mercury that may be still free to fall off. This method is much to be preferred when it is required to amalgamate a large number of plates. A very little mercury deposited at the bottom of the zinc division in the battery will suffice to keep the plate well amalgamated for a long time.

By adopting the process of amalgamation the commonest zinc can be rendered thoroughly serviceable for a greater or less period according to the degree of effectiveness with which the process has been carried out. As to its rationale, it appears evident that the function of the mercury is to homogenise the molecular arrangement by uniformly softening the zinc and forming with it a regular amalgam unassailable by pure sulphuric acid. The amalgam in an almost liquid state glides over and covers up any impure particles that have not been dissolved off by the washing process; as the zinc wears away these particles fall out and drop to the bottom of the cell to do no further harm.

The mercury does not enter into action with the acid or in any other way interfere with the efficient working of the cell, but on joining up the battery the acid attacks and dissolves the zinc more or less uniformly, the mercury eating its way inwards as the superficial zinc particles enter into the solution.

The circular form of battery is very extravagant in the matter of shelf or floor space, while the square or flat types, which have practically superseded the circular ones, are essentially compact, and are for that reason to be preferred. The square type was originally introduced by Dr. Muirhead. It consists generally of a wooden box or trough, into which five double or ten single cells of white glazed porcelain or ebonite are placed, when it presents a neat and compact appearance, as shown in fig. 19. Fig. 20 is a section of one of the single-cell porcelain vessels, fig. 21 illustrating the double-cell form. The latter is square and is very convenient. There is a little ridge along the bottom of each cell (see fig. 20) to keep the flat porous vessel in position. This porous vessel containing the copper plate is filled up with copper

FIG. 19.

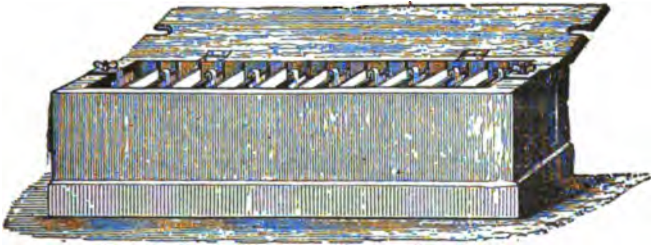


FIG. 20.

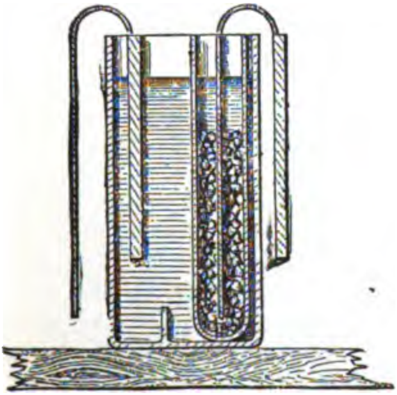
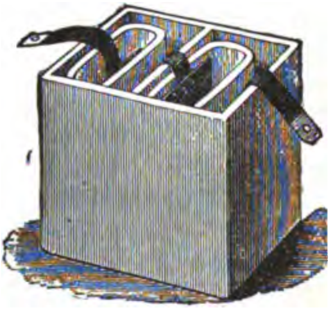


FIG. 21.



sulphate crystals, the zinc, which should be not less than ¼ inch thick (to allow for waste by local action), being suspended in the zinc sulphate solution. It will be noticed that the copper plate is attached to the zinc of the next adjacent cell. It is usual in practice to rivet one end of a copper strap on to the copper plate, the zinc being cast on to the other end of the strap. In this way expensive binding screws or terminals are dispensed with, and a good and substantial contact is ensured. The last zinc and the last copper are connected to brass terminals, which become respectively the negative and positive poles of the battery.

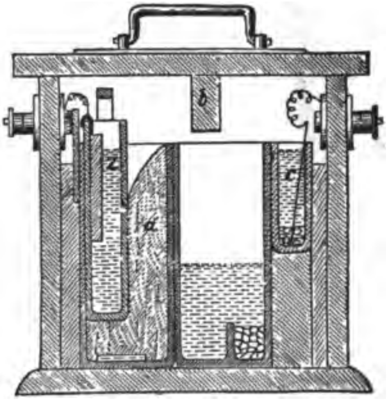
Nothing but clean water (hard water should, if possible, be avoided) is poured into the zinc division, but sufficient is added to bring it up to within about a quarter of an inch of the top of the zinc plate. The battery at the end of about twenty-four hours will be found to be in working order, the sulphate having dissolved in the copper division and enough passed through the porous partition to start the chemical action. Under these circumstances, then, a portion of the cupric sulphate that would otherwise be wasted is utilised to convert the water into a solution of zinc sulphate. If the battery is wanted for immediate use, the zinc cell must be filled with a weak solution of sulphate of zinc (or sulphuric acid), and the copper cell with a saturated solution of sulphate of copper; action then commences at once. It is often more convenient to dispense with the trough or box and place the cells side by side on a shelf. The advantage of this in an extensive battery room is apparent.

All porous pots should be dipped, top and bottom, in melted paraffin wax, so as by filling up the pores to prevent the solutions mingling too freely or rising to the top above the level of the liquids, and so allowing the water to evaporate and the salts to crystallise out. One side of the flat porous pots may also be paraffined with advantage—viz. the side which is remote from the zinc.

A porous pot which has been once used should not be allowed to get dry, as the crystals which form on drying chip it, and will soon render it useless.

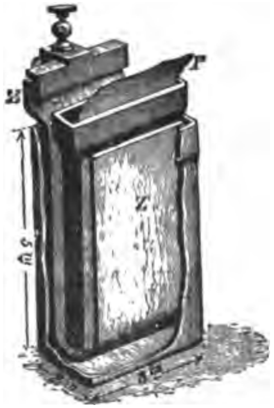
The Daniell cell, when in good condition, can be employed as a standard of electro-motive force, and owing to the ease with which the copper salt is decomposed, the cell possesses one great advantage over the Clark standard cell, in that it does not polarise when joined on short circuit, even when it is giving a more or less continuous current. It has, however, the disadvantage that for accurate measurement it requires a certain amount of attention which must be particularly directed to the zinc division, to keep it free from copper. A very handy and convenient form of Standard Daniell is that shown in fig. 22. In a square wooden box, provided with two terminals for connection, are three watertight chambers. When the cell is not in use, the copper plate *c* is removed to the right-hand chamber containing copper sulphate solution, the zinc plate *z* and the porous pot containing it being transferred to the left-hand chamber. This porous pot is supplied with a semi-saturated solution of zinc sulphate, the copper sulphate solution and its reserve of crystals being placed in the middle chamber. All that is then necessary to place the cell in working order is to remove the copper and the porous pot into the centre division. The stud *b* attached to the lid, prevents it being shut down unless the porous pot has been removed to the outer chamber. Such a cell will maintain an electro-motive force of 1·07 to 1·079 volts for a considerable time, providing that the copper and porous pot are removed to their respective idle chambers, between the tests.

FIG. 22.



We have seen that Daniell absorbed the freed hydrogen by causing it to reduce a metallic salt: Grove and Bunsen in their batteries oxidised the liberated hydrogen by means of an acid, water being produced by this hydrogen instead of sulphuric acid, as in the Daniell. In the negative division concentrated nitric acid is used, into which Grove dipped platinum foil, while Bunsen adopted gas-carbon. Zinc, as usual, constituted the positive plate in each case, the liquid placed with it being a solution of sulphuric acid. The diagram (fig. 23) shows the construction of the Grove. It is usually contained in a flat rectangular glass, porcelain, or ebonite vessel, porcelain being perhaps the best. The amalgamated zinc plate, z, is bent into a U-shape, and supports the flat porous pot which contains the platinum foil, P. By this arrangement each surface of the platinum has opposed to it a surface of zinc, the internal resistance being consequently very low. A strong solution of sulphuric acid (about 1 of acid to 7 or 8 of water) is poured into the outer cell and strong nitric acid having a specific gravity of 1·420 is placed in the inner cell with the platinum. The copper or brass connections or terminals should be lacquered except upon those surfaces which take part in the electrical circuit, to protect them as much as possible from the gases which are evolved during the working of the cell.

FIG. 23.



The action is in the first stage similar to that in the Daniell, but there is some diversity of opinion as to what actually transpires in the platinum division. Zinc sulphate is formed by the action of the sulphuric acid on the zinc, and the hydrogen which is thereby released reduces the nitric acid (HNO_3) to water and nitric peroxide (N_2O_4), which ascends as a gas into the air. This gas is distinguishable from all others by its dense brown appearance and its extremely pungent odour.

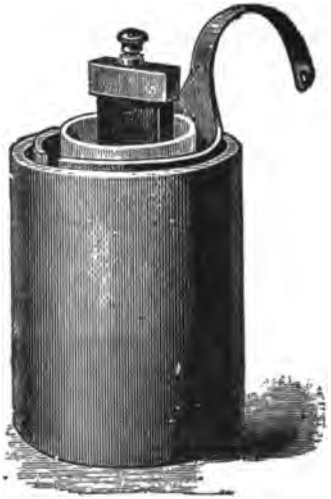
The chemical reactions may be represented by the equation—

$$Zn + SO_4H_2 + 2HNO_3 = ZnSO_4 + 2OH_2 + N_2O_4.$$

It will be noticed that the acid, which, to give the maximum strength of current, should be concentrated, must be seriously weakened as the current is produced. This results, in the first place, from the fact that every atom of hydrogen set free from the sulphuric acid decomposes a portion of the nitric acid, while in the second place the water which is formed dilutes and so weakens the remaining acid. The acid, which, when first poured in, should be quite colourless, is first turned brown by the peroxide, which is more or less soluble in the acid, changing subsequently to green, when it is practically useless.

The Bunsen cell, which is illustrated in fig. 24, is most frequently made in the circular form. The outer jar is of glazed earthenware or glass, and contains a solution of sulphuric acid, ordinarily in the proportion of 1 of acid to 7 or 8 of water, as in the Grove. Into this is placed a cleft zinc cylinder, and inside this is the porous cell, containing a rod of carbon, immersed in strong nitric acid. The porosity of the carbon enables it to present to the liquid a very extended surface, as compared with the platinum of the Grove cell.

FIG. 24.

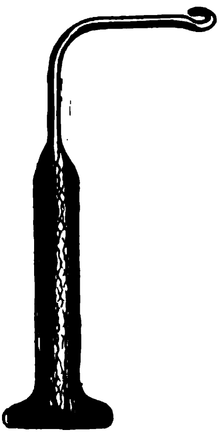


The action in the battery is identically the same as in the Grove, since the carbon and platinum remain chemically unaffected.

The Daniell and the Grove cells are the representatives of two extensive classes of battery. Daniell's has attained its high standard of popularity on account of its cheapness and its constancy. It is much more constant than either of those we have as yet mentioned. The Grove, on the other hand, is very powerful, but, owing to polarisation, it runs down very rapidly, and is not reliable for more than three to four hours at a time. It is, however, important to remember that if the negative plate and its acid are removed from the cell separately and allowed to stand for a time, the acid can be used again and the cell will give a current practically as good as before The same acid can be used three or four times before it is so reduced in strength as to materially affect the current, a state which, as already mentioned, is indicated by the greenish hue imparted to the acid. The chief use of the Grove cell in England is for experimental purposes. It has the advantage that it is very compact and portable. The Bunsen has a slightly higher electro-motive force, and it is somewhat cheaper than the Grove. As, however, it is generally constructed in the cylindrical form, it is much less convenient.

There are many forms of double-fluid bichromate batteries. In nearly all of them zinc and carbon are employed for the positive and negative elements respectively, the difference being, generally speaking, confined to the depolarising solution surrounding the carbon plate. In one of them, however, a great feature is made of the means adopted for keeping the zinc well amalgamated. This cell is known as the 'Fuller,' and it is usually put up in a round earthenware jar, in which is placed a comparatively small porous pot containing a zinc rod of peculiar shape, as shown in fig 25. The zinc is cast on to a stout copper wire which passes almost to the bottom of the rod and helps to keep it intact. Two or three ounces of mercury are placed in the porous pot, which, on the addition of the solution (dilute sulphuric acid), creeps up the surface of the zinc by the force of capillary attraction and so keeps it uniformly and automatically amalgamated. A small carbon plate is placed in the outer vessel in a solution of bichromate of potash, derived, however, from a stiff paste, of which a quantity is placed in the bottom of the cell, and which contains, probably, a quantity of free chromic acid, soda nitrate, &c. An unusually large quantity of this solution is generally provided in order to maintain its strength for a longer period of time than would be the case were the more usual proportions adopted. The chemical action is practically the same as that in the single-fluid bichromate cell. What is true of the nitric acid cells of Bunsen and Grove is also true, although, perhaps, to a less degree, with each and every form of bichromate of potash or of chromic acid cell—viz. that polarisation and the accompanying

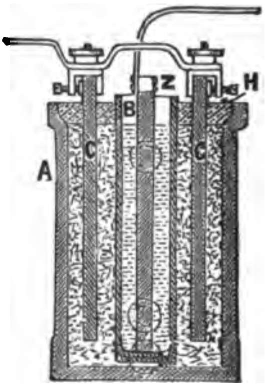
FIG. 25.



reduction in the electro-motive force, and therefore also in the current strength, sets in after the battery has been in use for a few hours more or less. The electro-motive force of the cell is, however, high, ranging from 1·9 to 2·15 volts. Its internal resistance is also very low, whence it finds considerable favour.

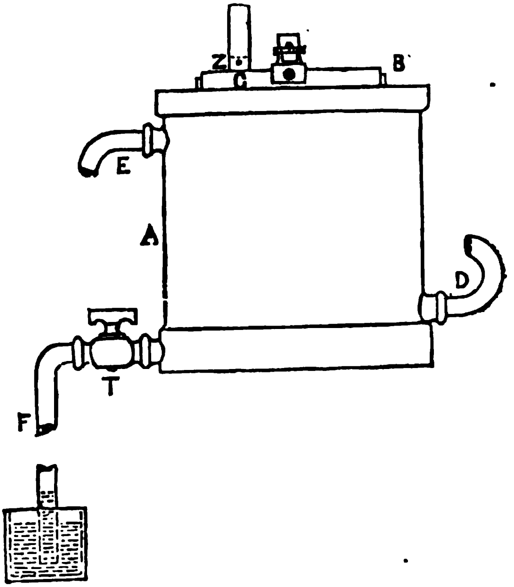
The most ingenious battery yet constructed for electric lighting purposes is probably that of Mr. A. René Upward, the principle of which will be gathered from figs. 26 and 27. The positive plate, Z, is of cast zinc immersed in water (which afterwards becomes zinc chloride), contained in the porous pot, B. The negative element consists of two carbon plates, C C, joined together and placed in the outer vessel, A, of glazed earthenware, the space between A and B being then closely packed with crushed carbon and sealed in with a layer of cement, H. Chlorine gas, which has considerable affinity for zinc, is led into the outer cell by the tube, D (fig. 27), and, passing between the small pieces of carbon, finds its way into the zinc division, where it enters directly into chemical union with the zinc forming zinc chloride, thus $Zn + Cl_2 = ZnCl_2$. Such of the gas as is not retained in the one cell passes through the outlet tube, E, to the bottom of the next cell. As the chloride of zinc solution passes through the porous partition, it accumulates to a very small extent at the bottom of the outer vessel, and thence, on the tap, T, being turned, it flows through the tube, F, into the receiver, G. There is, however, always sufficient water or solution in G to cover the end of the tube F to prevent air passing upwards into the cell. Such a cell, measuring 11½ × 5½ inches and 12½ inches deep, offers an internal resistance of about 0·2 ohm, and furnishes an electro-motive force of 2·1 volts.

FIG. 26.



In a later form each cell contains five cylinders of zinc joined together so as to give a large positive surface, the negative element consisting of eight carbon plates. The other details correspond to those shown in figs. 26 and 27. The inlet tube is connected direct to the apparatus in which the chlorine gas is generated, the outlet tube being connected to the inlet of the next cell, the outlet of which is in its turn connected to the bottom of the first of a series of vertical columns, made by carefully sealing together a number of ordinary earthenware drain-pipes.[1] The top of the first of these columns is connected to the bottom of the second, and so on, the top of the last of the series being provided with an outlet tube extending into the outer air. Chlorine gas is rather more than twice as heavy as air, so that as the gas first enters at the bottom of the cells it drives out the superincumbent air by ordinary displacement. Similarly with the reservoir columns, the first being filled with chlorine before any enters the second column, and so on. The connecting tubes are of lead, which is the most

FIG. 27.



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[1] In the earlier form of the battery, a very pretty and ingenious aspirator was connected to the battery which served the purpose of drawing the gas through as required.

durable material available, as it has only a feeble affinity for chlorine at ordinary temperatures. A piece of glass tubing is let into each of the lead pipes connecting the reservoir columns, and, the back of the glass being painted white, the presence of the chlorine is easily recognised by its distinguishing greenish-yellow hue.

There are various ways of generating chlorine, the method employed by Mr. Upward being that of heating a mixture of manganic oxide, sulphuric acid, and brine (sodic chloride). The reaction is represented by the equation :—

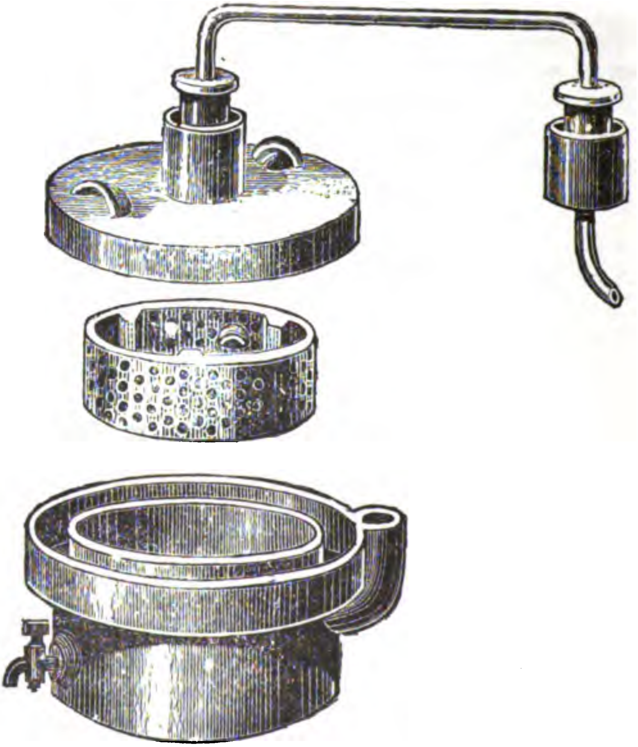
$$\underset{\text{Manganic oxide.}}{MnO_2} + \underset{\text{Sulphuric acid.}}{2SO_4H_2} + \underset{\text{Sodic chloride.}}{2NaCl} = \underset{\text{Sodic sulphate.}}{SO_4Na_2} + \underset{\text{Manganous sulphate.}}{SO_4Mn} + \underset{\text{Water.}}{2OH_2} + \underset{\text{Chlorine.}}{Cl_2}$$

The whole of the chlorine contained in the salt is thus reduced to the gaseous state.

The apparatus employed for the generation of the gas is illustrated in fig. 28. In a round earthenware pan is placed the perforated earthenware tray previously filled with the black manganic oxide, sufficient for two or three weeks' run. The cover is then placed in position and sealed with water run into the groove shown in the pan. The brine and acid, which are stored in jars, are supplied daily through the inlet tube shown on the right of the pan, the spent liquid being drawn off at the tap on the left, which is connected directly with the drain by means of a sealed pipe. The whole being placed in a sand bath, sufficient heat is supplied by a small gas jet or oil flame to bring about the required chemical changes. The gas is conveyed by the tube shown at the top to the first of the battery cells. When it is required to re-charge the retort with manganic oxide, it is flushed out with water (entering at the same aperture as the acid) to remove any trace of the chlorine gas. The lid and tray of spent oxide are then taken out and a spare tray filled with fresh oxide inserted and the lid replaced.

These cells might be joined up in a sufficiently long series to light a number of incandescent lamps directly, but that number would be limited owing to the comparatively high internal resistance of the battery. It is suggested, therefore, to employ only a couple of cells, and with them to charge, one by one, a number of secondary cells (see Chapter XIV.), the primary current being automatically switched from one cell to the next, after it has been charging it for a certain time. Clever in conception as this battery undoubtedly is, it is scarcely one that could be placed in the hands of inexperienced people, or be relied upon to maintain an electric light installation for any length of time. Chlorine gas, again, is very insidious, and its occasional escape in greater or less quantities could hardly be prevented. Were it perfect, however, there would only be a limited field open for its employment, and that on a very small scale. Its expense would prevent it ever entering

FIG. 28.



into competition with the dynamo machine for work on a large scale.

There are, of course, a vast number of cells which we have not considered it necessary to describe here, but they may generally be placed under one or other of the typical heads, viz. the Daniell with a metallic salt, or the Grove with an acid, in the negative division. The general difference is that the latter polarises more or less rapidly, while the former does not polarise, but is kept constant by the metallic deposit upon the negative plate.

Primary batteries are of but little service in electric lighting. They are, of course, valuable for testing purposes, but as sources of current for the electric light they are altogether out of place, except for small isolated work, owing to the fact that zinc, which is in every case used as the positive plate, and which, being consumed in the generation of the current, corresponds to the coal consumed in an engine, is very many times dearer than coal. Even were expense a question of minor importance, there still remains the fact that primary batteries are very troublesome to maintain, and more often than not give off noxious fumes, which are also as a rule highly corrosive. What is really wanted, putting aside altogether the question of expense, is some simple form of cell, of which the constituents can be easily obtained and replaced; from which no injurious fumes can arise; which shall have a high electro-motive force and a low internal resistance, and be fairly constant withal.

There are three considerations that have to be taken into account when determining what kind and what number of cells it would be most advisable to employ for any particular purpose—viz. the relative constancy and electro-motive force, and the ratio between the internal resistance of the cell and the external resistance, or the resistance of the connecting wires and apparatus. It will have been gathered that there is in this matter of electro-motive force and constancy considerable variation. We will not enter here into the matter of expense, for in the end that which is the best cell for any particular purpose generally proves to be also the cheapest. The internal resistance is, however, an important factor. If it were negligible, it would, for example, be possible to maintain a current of one ampere by one Daniell cell working through an external resistance of one ohm, for as (see Chapter II.)

$$\text{C} = \frac{\text{F}}{\text{R}}, \text{ then } \frac{1 \text{ volt}}{1 \text{ ohm}} = 1 \text{ ampere.}$$

But the average Daniell cell offers four ohms resistance, so that the current, where R is the external resistance of one ohm, and r the internal resistance, would be

$$\frac{\text{E}}{\text{R} + r} = \frac{1}{1 + 4} = \cdot 2 \text{ ampere };$$

and if we were to attempt to increase this current materially by the addition of, say, nine other similar cells, we should fail, for then

$$\frac{10\text{E}}{\text{R} + 10r} = \frac{10}{1 + 40} = \cdot 25 \text{ ampere nearly.}$$

Similarly, with 100 such cells through this unit resistance—

$$\frac{100\text{E}}{\text{R} + 100r} = \frac{100}{1 + 400} = \cdot 25 \text{ nearly.}$$

We see, then, that increasing the number of cells in this way, when the external resistance is low, produces no correspondingly good effect, for the simple reason that, although we might proportionally increase the electro-motive force by so doing, we should at the same rate increase the circuit resistance. As a matter of fact, no ordinary Daniell cell or battery can possibly develop a current of one ampere, its internal resistance being too high.

On the other hand, were we to employ Grove cells (which for simplicity we will assume to have an electro-motive force of 2 volts per cell), the advantage of increasing the number of cells on a low resistance circuit soon becomes apparent. For example, with an external resistance of 1 ohm and an internal resistance of ·2 ohm per cell, one cell would give us,

$$\frac{\text{E}}{\text{R} + r} = \frac{2}{1 + \cdot 2} = 1 \cdot 6 \text{ amperes.}$$

Two such cells would produce

$$\frac{2\text{E}}{\text{R} + 2r} = \frac{4}{1 + \cdot 4} = 2 \cdot 85 \text{ amperes.}$$

And three cells

$$\frac{3\text{E}}{\text{R} + 3r} = \frac{6}{1 + {\cdot}6} = 3{\cdot}8 \text{ amperes nearly.}$$

Similarly, four cells would give 4·4 amperes and five cells would yield 5·0 amperes. But from ten cells we should only get

$$\frac{10\text{E}}{\text{R} + 10r} = \frac{20}{1 + 2} = 6{\cdot}6 \text{ amperes.}$$

While with 100 such cells the current would be

$$\frac{100\text{E}}{\text{R} + 100r} = \frac{200}{1 + 20} = 9{\cdot}5 \text{ amperes,}$$

showing again that as the internal resistance approaches or exceeds the external, the proportional current from the battery is reduced. When, however, the external resistance is relatively high, say 1,000 ohms, the battery resistance becomes proportionally low, and, therefore, to a certain extent, negligible. The current from one Daniell cell would be

$$\text{C} = \frac{\text{E}}{\text{R} + r} = \frac{1}{1000 + 4} = {\cdot}000996 \text{ ampere.}$$

With ten cells we should get,

$$\frac{10\text{E}}{\text{R} + 10r} = \frac{10}{1000 + 40} = {\cdot}00961 \text{ ampere,}$$

or, practically, a current of tenfold strength.

Similarly, with a battery of 100 cells, we should get

$$\frac{100\text{E}}{\text{R} + 100r} = \frac{100}{1000 + 400} = {\cdot}0714 \text{ ampere.}$$

Again, one Grove cell would give through 1000 ohms

$$\text{C} = \frac{\text{E}}{\text{R} + r} = \frac{2}{1000 + {\cdot}2} = {\cdot}002 \text{ ampere,}$$

and ten cells would give

$$\frac{10\text{E}}{\text{R} + 10r} = \frac{20}{1000 + 2} = {\cdot}0199 \text{ ampere.}$$

From 100 cells we should get—

$$\frac{100E}{R + 100r} = \frac{200}{1000 + 20} = \cdot 196 \text{ ampere.}$$

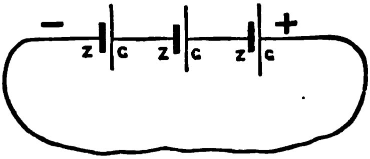
With either the Daniell or the Grove the strength of the current increases in almost the same ratio as the number of cells when the external resistance is high. But as the Grove is vastly inferior to the Daniell in constancy, and as it is a very expensive form of battery, the deduction is that Daniell cells should be used for circuits of high resistance, compensating for their lower electro-motive force by a corresponding increase in numbers. On the other hand, the Grove, in consequence of its low internal resistance, is better adapted for circuits of low resistance.

The internal resistance, however, of different cells of any particular type varies inversely as the size of the plates (counting only the active or opposed surfaces). It also varies directly as the distance between them (making due allowance for the resistance of the porous pot, which would, of course, have a constant value unless varied in size or thickness). The meaning of this is plain, for if we were to double the size of the plates we should halve the resistance and proportionally increase the current strength.

The same object is attained by joining cells in 'parallel.' So far we have only considered them as joined in series, that is to say, the copper of one cell joined to the zinc of the next and so on. Under such circumstances the electro-motive force of the battery is equal to the sum of the electro-motive forces of the various cells. If the coppers of two cells are joined together, and likewise the zincs, and the two junction wires connected to the external circuit, a current will be developed by an electro-motive force equal to that of one cell, the joint resistance of the two equal cells being half that of one of them used separately. The arrangement is, in fact, equivalent to doubling the size of the plates.

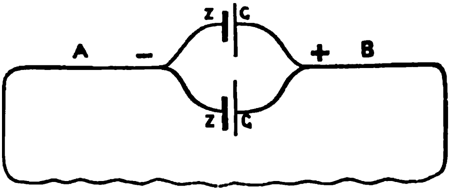
This will, perhaps, be made clearer by a reference to the diagrams, figs. 29, 30, and 31. Fig. 29 represents a battery of three cells joined in series, the short thick strokes representing the zinc or positive plates, and the long thin ones the copper or negative plates. Fig. 30 shows two cells joined up in parallel. If they are both of exactly the same electro-motive force, no current can flow from C to C or from Z to Z, but on joining the external wires A and B together, a current would be generated by each cell and

FIG. 29.



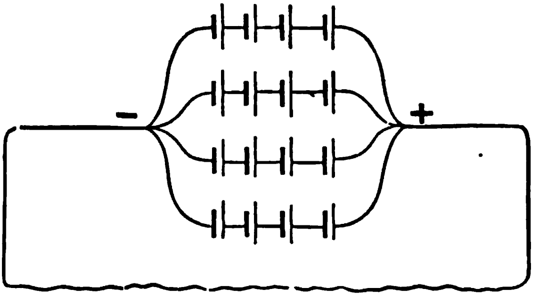
pass through the external circuit from B to A. As already stated, the joint resistance of these two cells would be half that of one

FIG. 30.



of them. With a low external resistance the current strength would be increased proportionally. In fig. 31 are shown sixteen

FIG 31.



cells divided into four sets of four cells each, the sets being joined up in parallel. On completing the external circuit a current will flow, having an electro-motive force equal to that of four cells, but the battery resistance will be only one-fourth of that of four cells.

The joint resistance of any number of parallel batteries is equal to $\frac{rs}{B}$, where r is the resistance per cell, s the number of such cells joined up in series in each individual battery, and B the number of such batteries joined together in parallel. This is simply an application of the law that with a number of conductors, N, of uniform resistance, R, joined together in parallel, their joint resistance is equal to $\frac{R}{N}$. For rs is the total resistance of each of the batteries joined together in parallel. This arrangement is sometimes very advantageous; for example, if sixteen Daniell cells, each of 1 volt electro-motive force and 4 ohms internal resistance, are employed in series for a circuit of 4 ohms external resistance, the current will be

$$\frac{16}{4 + 64} = \cdot 235 \text{ ampere} \quad . \quad . \quad . \qquad (1).$$

By dividing the cells into two sets of eight cells each and joining these in parallel, the current is increased, thus

$$\frac{8}{4 + 16} = \cdot 400 \text{ ampere} \quad . \quad . \quad . \qquad (2).$$

On rearranging the cells, as shown in fig. 31, the current becomes

$$\frac{4}{4 + 4} = \cdot 500 \text{ ampere} \quad . \quad . \quad . \qquad (3).$$

Pursuing this plan any further, however, results in a diminution of the current; for example, if eight sets of two cells each are joined in parallel, we get

$$\frac{2}{4 + 1} = \cdot 400 \text{ ampere} \quad . \quad . \quad . \qquad (4).$$

While with the whole of the sixteen cells joined in parallel we get only

$$\frac{1}{4 + \cdot 25} = \cdot 235 \text{ ampere} \quad . \quad . \quad . \qquad (5).$$

With circuits of comparatively low external resistance there is, therefore, a best possible arrangement of the cells to give the strongest possible current, and with any given number of cells this arrangement is arrived at when the internal resistance is equal to the external, or when $R = \frac{rs}{B}$.

Such an arrangement is not, however, economical; nor, indeed, is any arrangement, unless the external resistance is considerably in excess of the internal. As has been already stated, the strength of the current is the same in all parts of the circuit, consequently in (1) sixteen times as much zinc, &c., is consumed in the sixteen cells as would be consumed in a single cell capable of maintaining an equal current. In (3), however, each set of four cells must be considered as a separate or branch circuit, and only one-fourth of the current flowing in the external circuit would flow through each of these separate sets. The external current is approximately twice as strong as in (1). Therefore the individual current in each cell and the consequent consumption of zinc is only half as great. In (5), where there are sixteen cells in parallel, a current is produced equal to that resulting from a battery of sixteen cells in series, but, the cells being joined up in parallel, only one-sixteenth of this current flows through each cell, so that the total consumption of zinc in the sixteen cells is equal to that in but a single cell in (1), clearly demonstrating the advantage, from an economical point of view, of using batteries much lower in resistance than the wire or apparatus through which the current has to flow.

One important feature concerning the proportion between the gross electro-motive force of the battery and the difference of potential it can maintain in any given external circuit requires careful consideration, for it is a feature that is frequently lost sight of. It was pointed out in Chapter II. that in any given circuit the fall of potential varies directly as the resistance, so that in (1), where the internal bears to the external resistance the proportion of 16 to 1, only one-seventeenth of the 16 volts developed by the battery is available in the external circuit, the remaining sixteen-seventeenths being absorbed in overcoming the resistance of the battery. In (3) the resistances outside the battery being equal to that inside, the electro-motive force of 4 volts developed is halved, 2 volts being available for the external circuit Similarly in (5), the available electro-motive force for the external circuit is sixteen-seventeenths of a volt (the gross electro-motive force developed being 1 volt), or equal to that produced by the sixteen cells joined up in series, as in (1), where, as already shown, the consumption of materials is sixteen times as great, and, speaking generally, we may say that

$$P = E \frac{R}{R + r}.$$

Where E is the electro-motive force developed by the battery, R is the external resistance, r is the internal resistance, and P the available potential difference at the terminals of the battery. For example, with a battery, as in (4), whose internal resistance is 1 ohm working through an external resistance of 4 ohms, and having an electro-motive force of 2 volts, the available potential difference will be

$$P = 2 \frac{4}{4 + 1} = 1{\cdot}6 \text{ volts.}$$

The available potential difference can also be ascertained in another way which does not involve the necessity for ascertaining the external resistance. Ohm's law declares $C = \frac{E}{R}$ or, $E = C\,R$. And this is true either of a complete circuit or simply of a part of a circuit. If, for instance, in a circuit of known or unknown resistance the current strength is found to be, say, 1·5 amperes, and that a portion of the circuit offers a resistance of 3 ohms, then the fall of potential, or the electro-motive force absorbed, in that portion of the circuit will be

$$E = C\,R = 1{\cdot}5 \times 3 = 4{\cdot}5 \text{ volts.}$$

If the known resistance is that of the battery (r), it follows that 4·5 volts will be the electro-motive force absorbed by the battery, and if that is deducted from the total electro-motive force developed (say, 20 volts), the remainder will be the available potential difference for the external circuit, or

$$P = E - C\,r = 20 - (1{\cdot}5 \times 3) = 15{\cdot}5 \text{ volts.}$$

Occasion sometimes arises for substituting one form of battery for another without making any appreciable change in the current strength. If the internal resistance were negligible, this would, of course, be a matter of no difficulty; but even when it is requisite to make allowance for the battery resistance, a simple formula can be employed to ascertain the number of cells necessary to develop a given current strength. For example, suppose that a battery of 100 cells, with an electro-motive force of 1 volt and an internal resistance of 4 ohms per cell, sends a current through an external resistance of 400 ohms, then the current will be

$$\frac{100\text{E}}{100r + \text{R}} = \frac{100}{400 + 400} = \cdot 125 \text{ ampere.}$$

Substituting some other form of battery with an electro-motive force of 2 volts and an internal resistance of 1 ohm, and letting n be the number of such cells necessary to develop 0·125 ampere, then

$$\frac{n2}{n \times 1 + 400} = \cdot 125 = \frac{1}{8} \text{ ampere,}$$

that is to say,

$$\frac{2n}{n + 400} = \frac{1}{8},$$

or,

$$16n = n + 400$$

$$15n = 400$$

$$n = \frac{400}{15} = 26{\cdot}6.$$

Twenty-seven of these 2-volt cells would maintain in the circuit a current of

$$\frac{27\text{E}}{27r + 400} = \frac{54}{27 + 400} = \cdot 126 \text{ ampere.}$$

Twenty-six cells would be insufficient for the purpose. This formula also possesses the advantage of providing the same potential difference at the terminals of the battery, as well as that of furnishing the number of cells necessary to develop an equally strong current.

CHAPTER IV.

MEASUREMENT OF CURRENT STRENGTH.

HAVING in the preceding chapters shown how a current of electricity can be generated and maintained, and having also explained the various units by which we can measure that current, as well as the resistance, and the pressure or electro-motive force which maintains the current, it behoves us now to turn our attention to the methods of making such measurements and the consideration of the laws involved. In order to make the student's progress at this difficult stage as easy as possible, we will approach the subject experimentally.

If a wire, A B (fig. 32), carrying a current is brought near another wire, C D, also carrying a current, it is found that there is a decided action between the two wires. If the currents are flowing in the same direction, as shown by the arrow-heads in fig. 32, the wires are attracted one to the other. On the other hand, if the currents travel in opposite directions, as in fig. 33, repulsion ensues.

FIG. 32.

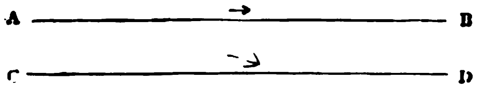
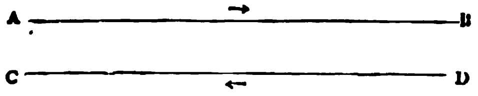


FIG. 33



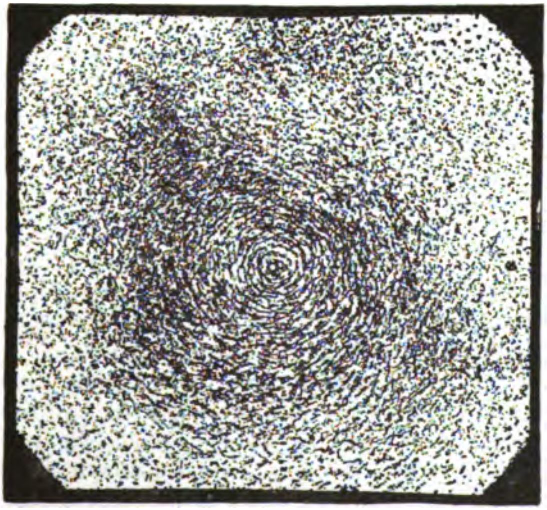
The force of this attraction or repulsion depends, among other considerations, upon the strength of the current. It would be possible, therefore, to take advantage of this effect as affording a means of estimating or measuring current strength, and a device for so doing will be described presently.

Now it is impossible for any action to take place between the two wires without the aid of some intervening medium to transmit the force. This medium is the same as that which transmits the electrical stresses in the other or static state of electricity, that state in which a body affected by it is said to be electrified or charged with electricity, and is, in all probability, the light-carrying ether.

Although it is difficult to understand the precise action in this case, it is easy to show experimentally the direction in which the force acts.

If we thread a wire which is carrying a current through a piece of cardboard, and sprinkle iron filings on the cardboard, they will arrange themselves in concentric circles round the wire as shown in fig. 34. This arrangement is caused solely by the current and may be observed at any part of the wire. The lines thus

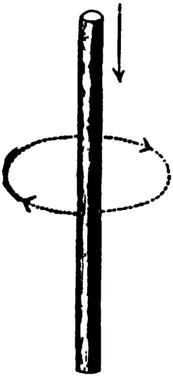
FIG. 34.



marked out, which show the direction in which the force due to the current acts, are called 'lines of force.'

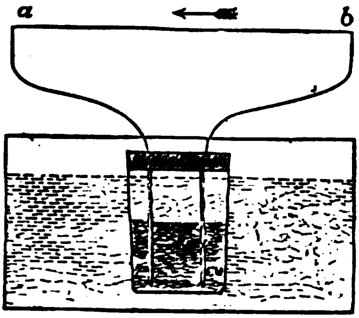
As in the case of the imaginary lines considered in Chapter I., it is necessary to assume for them a certain direction. That direction along a line of force, indicated by the arrows in fig. 35, is called the 'positive' direction. The direction can be impressed upon the memory by thinking of the act of using a corkscrew. If the longitudinal direction of the screw, either *into* or *out of* the cork, be taken to represent the direction of the current, then the positive direction of the lines of force will be that in which the handle rotates, so that if in fig. 35 the downward direction of the current were reversed, the positive direction of the lines of force would be in the opposite direction to that indicated by the arrow-heads. The space around the wire in which the effect of the current is perceptible is called an 'electro-magnetic field,' and it is important to remember that the strength of this field is exactly proportional to the strength of the current producing it. It extends from the axis of the wire as a centre throughout the surrounding space, but as the distance from the wire increases, the effect is weakened until it at last becomes so feeble as to be imperceptible. The lines of force traversing this field obey precisely the same laws as those laid down for the lines due to a static charge, and the interaction between two sets of lines of force can always be predicted by remembering that their universal tendency is to coincide in direction and to shorten themselves.

FIG. 35.



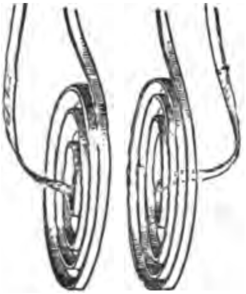
Reverting to the experiment with the two wires carrying the currents, it may be said that the force exerted between them always tends to move them so that they shall take up such a position that the currents flow in the same common direction (as in fig. 32) and that the wires as nearly as possible coincide. To prove this, it is necessary to allow at least one of the wires to be capable of moving freely and with as little restraint or friction as possible. This can be done by means of a simple device for constructing a movable or floating battery cell. Let a cork be fitted to a small glass beaker partly filled with diluted sulphuric acid, and through the cork pass wires carrying thin strips of zinc and copper or silver, completing the circuit externally by means of a stiff but not too heavy piece of wire, as shown in fig. 36. The small beaker cell can then be placed in a larger beaker, or any other convenient vessel full of water, and, unless too much acid solution has been placed in the smaller beaker or the solid portions are made unnecessarily heavy, the cell will float readily upon the water. If a wire carrying a strong current is placed parallel to the straight part of the wire, *a b*, so that the currents flow in opposite directions, the wire *a b* will be repelled, and, the cell floating away, will turn completely round, so that the currents flow in the same direction; it will then be attracted until *a b* lies as near as possible to the other wire.

FIG. 36.



These effects may be increased by increasing the length of the wires, but very long straight wires would be cumbersome and, in fact, impracticable. It is, therefore, more convenient to coil them up into flat spirals (fig. 37), covering the wire with silk, cotton, or some insulating material, to prevent adjacent convolutions getting into contact. The effect between the spirals will be identically similar to that between the same two wires straightened out. For many purposes, however, it is preferable to coil the wire into a long spiral or helix. In fig. 38 one of the helices, A B, is floated in a manner similar to that adopted in fig. 36, the other helix, *a b*, being placed near it. The action between two such helices is very decided, and, being of exactly the same character as that between the straight wires

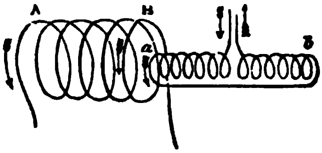
FIG. 37.



or flat spirals, may be predicted by remembering the laws we have just stated.

If the currents are flowing in opposite directions round adjacent ends of the spirals or helices, repulsion will take place, and the floating helix, moving more easily than the other, will recede, and, turning completely round on its vertical axis, will approach with its opposite end to the fixed spiral, as in fig. 38. The currents will then be flowing in the same direction, and the floating helix being comparatively large and its movements not restricted, it will not come to rest until it has threaded itself on to or over the other spiral. Such a spiral or helix of wire acts as if the force resided at its extremities, which are termed its 'poles,' and it is for this reason that this form of spiral is called a solenoid.

FIG. 38.

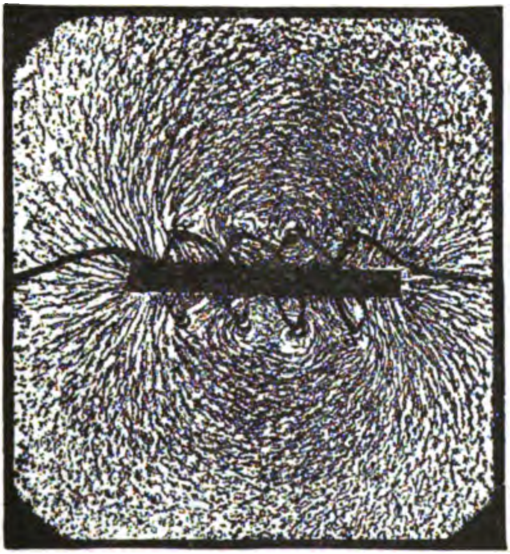


Now the strength of an electro-magnetic field may be measured by the density of its lines of force or the number contained in a given area. From the experiment shown in fig. 34, it is clear that the lines are much denser near the wire than at a distance from it. This is also the case when the wire is coiled up into a helix. The greater part of them there form little circles, closely embracing the wire from which they are generated, and comparatively few of these circles of force pass through the space at the ends or poles of the solenoid, where the force, generally speaking, appears to be concentrated. It will be evident that if we can by any means divert the circles of force so as to compel more of them to pass through the ends of the solenoid, then its effective strength will be greatly increased.

Experiment has demonstrated that iron offers a far easier path for these lines of force than the air does—so much easier, in fact, that they will alter their circular shape and extend a considerable distance from their respective portions of the wire in order to pass through a piece of iron. This affords us a ready means of leading the lines to, and concentrating them at almost any point we please. It may be mentioned that the relative facility with which the lines of force are propagated by good soft iron, or the electromagnetic conductivity of the iron as compared with that of air, may be as high as 20,000 to 1.

If, then, we place a bar of iron inside a solenoid, a large percentage of the lines of force lose their circular form, and, passing through this iron 'core' (as it is called), they leave it at its ends to complete their excursion round the wire from which they were generated. An example of this action of iron is shown in fig. 39,[1] which illustrates the field developed by a powerful current travelling through a solenoid of a few turns, having a core of compara-

FIG. 39.



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[1] We are indebted to the proprietors of *Engineering* for permission to reproduce figs. 39 to 42.

tively small dimensions. Were a larger or more massive core to be introduced, even more of the lines of force would extend themselves through the iron instead of circulating in the immediate vicinity of the wire.

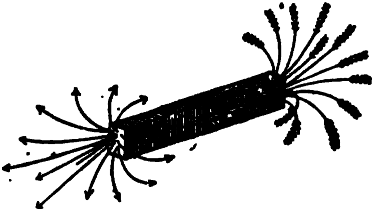
Fitted with these iron cores, the strength of the action between two solenoids is enormously increased. But here we must issue a word of warning. It must not be supposed that because we thus increase the polar strength of the solenoid, we have even in the slightest degree augmented the electro-magnetic force itself. With a given current and a given length of wire, that force is a constant quantity, the sum total of which cannot, in any sense of the word, be increased by the addition of a mass of iron, or even by any variation in the disposition of the wire, whether we wind it into a spiral, a solenoid, or use any other device. Were we able to augment the total force by any of these means, there would be an end to the law of the conservation of energy, which, as has already been pointed out, declares that when any one force is produced or developed it can only be at the expense of an equal amount of energy previously existing in another or a similar form. Force is indestructible; neither can we create it. The doctrine, therefore, so frequently laid down that the introduction of an iron core increases the electro-magnetic strength of a coil of wire, is misleading. The only means of increasing that strength or force is by increasing the current, or, what amounts to the same thing, by increasing the length of wire and increasing the battery power in sufficient proportion to maintain the same current strength. Let us state positively, even at the expense of a little reiteration, that what we really do, by the introduction of the iron core, is to concentrate a much larger proportion of the available force at those points where it acts at the greatest advantage, namely, at the poles of the solenoid. We would impress upon the student the necessity for ever keeping these facts clearly in mind.

The amount of attraction or repulsion exhibited by the solenoids furnished with their iron cores might be used as a means of measuring current strength, but the arrangement is not a convenient one, owing chiefly to the difficulty in obtaining perfect freedom of motion, the liability of variation in the current strength, and the varying properties of the iron.

Were it not for these disadvantages we could keep the electro-magnetic force of one of the solenoids constant, and send the currents to be compared and measured through the other. But here Nature comes in to aid us, for it is found that if a piece of *hard* iron or steel is used as a core for the solenoid, it retains more or less permanently a large portion of the electro-magnetic properties originally produced by the current. The power or ability of retaining such effects or properties is known as the 'retentivity' of the iron or steel, and depends entirely upon its chemical composition and mechanical or molecular structure. This retentivity is the same property as that hitherto known as 'coercive force,' which was certainly a misnomer and a libel upon the metal. If retentivity corresponds to anything at all, it is to *inertia* rather than to anything that can fairly be described as coercive. The similarity to mechanical inertia is seen in the fact that those samples which transmit the lines of force freely, retain scarcely any of the influences producible by them, while, on the other hand, hard iron and steel, which resist the propagation of the lines of force, resist equally well the vanishing of these lines after the cessation of the current which called them into existence.

A piece of iron or steel which acquires and so retains the power of acting as a solenoid, is called a permanent magnet, or simply a magnet, and its extremities are also called poles. The lines of force still enter and leave the steel as they did before it

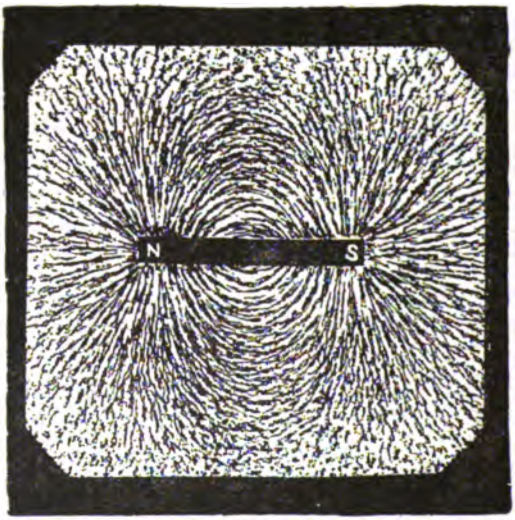
FIG. 40.



was removed from the helix, the direction being shown in fig. 40. The end, S, at which they enter is called the south-seeking pole of the magnet, and the other its north-seeking pole.

The actual arrangement imparted to iron filings sprinkled on a sheet of paper placed over a permanent steel magnet is beautifully illustrated in fig. 41. Such a distribution of the filings would take place in any plane parallel to the axis of the magnet, for the lines of force radiate from the poles similarly in all directions. The

FIG. 41.



distribution observed when the paper is placed on the end of the magnet and at right angles to its axis is shown in fig. 42.

If we know the direction in which the current passes round a piece of iron or steel, it is easy to predict the direction of its polarity; for if we look at the end of the bar and the current is then flowing round it in a right-handed direction, as in fig. 43, that end will be a south-seeking pole; but if the current flow in a left-handed direction, as in fig. 44, that end will be a north-seeking pole.

It is the practice to enter into a detailed description of the difference between right- and left-handed helices with a view to facilitating a recollection of the electro-magnetic polarity. Thus a left-handed helix (fig. 45) is one in which, from whichever end the current enters, it will travel in the opposite direction to that taken by the hands of a clock, and will develop north-seeking polarity at the end at which it enters and south-seeking polarity

FIG. 42.

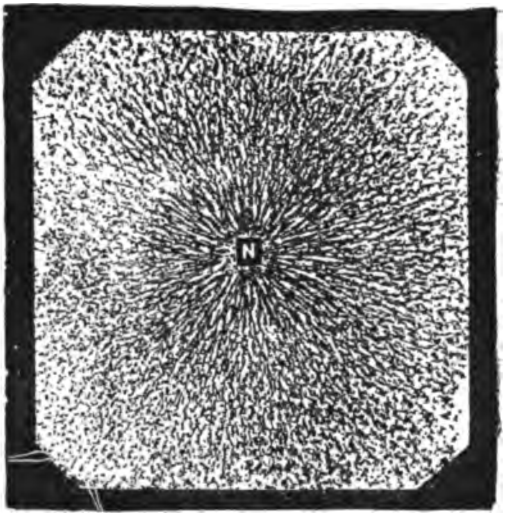


FIG. 43.

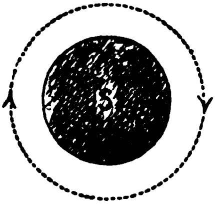


FIG. 44.

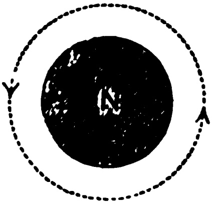
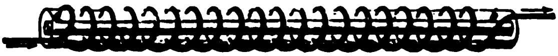


FIG. 45.

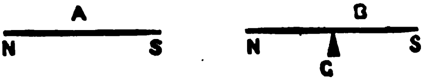


at the end of emergence. Conversely, a right-handed helix (fig. 46) is one in which the current will travel round in the same direction as the clock-hands. In this, the entering end becomes a south pole and the other a north pole. But all this is superfluous. It is sufficient to regard the cause and effect in the way indicated in the preceding paragraph.

FIG. 46.

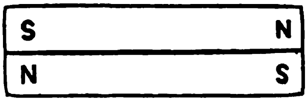
It is noteworthy that two magnets act one upon the other in precisely the same manner as two helices or a helix and a magnet, for in every case the movement or motion imparted is such as will tend to make the lines of force coincide. Thus, if one magnet, A (fig. 47), is brought near another, B, which is suspended by a thread or pivoted on a needle-point at C, so that it can turn freely about its centre, the force exerted between them will endeavour to make the suspended needle take up such a position as to allow the lines of force due to both magnets to pass through them in the same direction. This will happen when the magnets are in line and when their opposite poles are adjacent, as shown in fig. 47. In other words, there will be repulsion between similar magnetic poles and attraction between dissimilar ones.

FIG. 47.



If, however, both magnets are allowed perfect freedom of motion, their ultimate position will be that shown in fig. 48, the magnets then lying side by side with their dissimilar poles adjacent. In this position the coincidence of the lines of force is at a maximum, that is, the lines due to each magnet turn round at the ends and pass through the other, and in so doing assume the easiest path for their completion. If pieces of soft iron, called armatures

FIG. 48.



or keepers, were placed across the extremities of the magnets, the circuit of the lines of force would be continued through them to such an extent that few or none of the lines would traverse the air. These armatures are, however, rarely made properly, their mass being far too small, and their shape far from the best possible; but this point we will deal with more fully in Chapter VII.

The strength of a magnet pole can be estimated by measuring the force with which it attracts or repels another pole, the force being equal to the product of the two polar strengths; or, if M represents the strength of one pole, and M_1 the strength of the other, similarly magnetised, the force of their repulsion will be $M \times M_1$. This force of repulsion is not, however, the same at all distances, but varies inversely as the square of the distance, so that we might express the force f, between two magnet poles, by the simple formula,

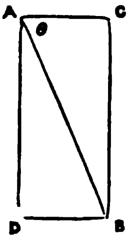
$$f = \frac{M \times M_1}{d^2},$$

where d equals the distance in centimetres between the poles. It is important to bear in mind that the distance between the two poles of each magnet should be as great as possible—or, in other words, that the magnet should be as long as possible—to minimise the error that would be produced by the ever-present tendency of the remote poles to act contrariwise to the adjacent ones.

We have already defined the dyne as the unit of force, and the magnet pole of unit strength is such a one that if placed at a distance of one centimetre from a similar and equal pole, it will repel it with a force of one dyne. Consequently, the strength at any point in any field can be determined by measuring, in dynes, the repulsion at that point of a magnet pole of unit strength. In every case, then, the force acting upon a magnet pole is found by multiplying the strength of the pole by the strength or intensity of the field in which it is placed. In order to compare the strengths of magnetic fields by the relative densities of the lines of force, it is assumed that a field of unit strength contains one line of force per square centimetre.

The earth itself is practically a huge misshapen or irregular magnet, and behaves as such, acting as if its poles were situated relatively near, but actually at some distance from, the geographical poles. If a magnet needle were suspended so that it could turn freely in a *vertical* plane, it would, with a plane of rotation east and west, point vertically downwards with its north pole; but if the plane of rotation were north and south, the needle would, in London, come to rest with the north-seeking pole dipping downwards, and making an angle – known as the angle of inclination or dip—of about 67½° with the horizon. If another magnet were suspended or balanced on a pivot in a horizontal plane, the needle would set itself approximately north and south, the north-seeking pole pointing to the north magnetic pole of the earth. The axis of the magnet—that is, the straight line joining its two poles—would actually make an angle—known as the angle of declination · of about 18°, with the geographical meridian passing through its centre. It will be observed that there is here a case of attraction between the north pole of the earth and the north-seeking pole of the magnet; but this is no contradiction of the law that similar poles repel and dissimilar attract, inasmuch as the magnetic properties of the north pole of the earth are in all respects the same as those of the south-seeking pole of a magnet. The earth's total magnetic force can be resolved into two components at right angles to each other, one acting in a vertical direction, tending to depress the north-seeking pole of the needle, the other acting in a horizontal direction and striving to make it point north and south. Their relative values may be found by the familiar parallelogram of forces (see fig. 49). The line A B is drawn making an angle θ with the horizontal equal to the angle of inclination, and the right-angled parallelogram which has A B for a diagonal completed with its sides horizontal and vertical. Then, if A B represents in length the magnitude of the total magnetic force, A C and A D will be proportional to the horizontal and vertical components respectively.

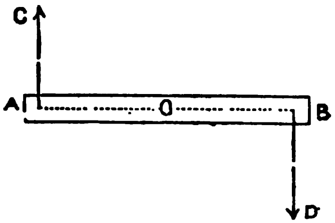
FIG. 49.



When the magnet is so balanced that it can only move in a horizontal plane, then a large proportion of the force—viz. the vertical component—is simply exerted in pressing the magnet on its support. The remainder, or the horizontal component only, is effective in making the magnet point towards the magnetic north and south. On the other hand, when the plane of a dipping needle is at right angles to the magnetic meridian, or to the direction of the earth's lines of force, the vertical component only is active, and the magnet points vertically downwards, the horizontal component spending its force in pressing the pivots against their bearings, vainly striving to urge the needle round into the direction of the dip. A horizontally balanced magnetic needle is useful in pointing out the direction of these north and south magnetic poles of the earth.

In consequence of the immensity of the earth as a magnet, its magnetic field is practically uniform over any small space—that is, its lines of force are *parallel* and *equidistant*. It follows, therefore, that the poles of a needle floating on water are attracted or repelled with equal force in any position, and, as a consequence of this, the needle does not move bodily towards the north pole of the earth, but is simply directed so as to point north and south. It may be stated that it is a well-known law in mechanics that when two equal forces, parallel but opposite in direction, act at the ends of a rigid bar, they tend to turn it round its centre. The turning effect is greatest when the forces act at right angles to the bar, as do C and D in fig. 50, A B being the rigid bar. The amount of this turning effect M is equal to the sum of each of the two forces multiplied by its distance from the centre—that is,

FIG. 50.



$$M = (C \times OA) + (D \times OB)$$

whence, C being equal to D,

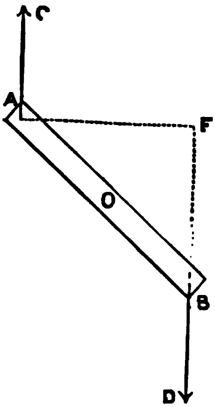
$$M = C(OA + OB)\text{—that is, } M = C \times AB,$$

or the product of one of the equal forces into the perpendicular distance between them.

Such a pair of equal forces is called a couple, the perpendicular distance between their direction being called the arm of the couple; and the turning effect, M, as measured by the product of one of the forces into the arm is the moment of the couple. As the bar turns round or rotates, the moment M is decreased, the forces being the same but acting at less advantage—in other words, the *leverage* is reduced. This will be more evident from a consideration of fig. 51, where the moment of the couple is $C \times AE$, the new perpendicular between the forces.

Reverting once more to the experiment with the floating needle, if we call the strength of one of the poles of the needle m, and let H represent the horizontal component of the earth's magnetic field, then the force acting on each end of the needle is $m \times H$. If we place the needle so as to point east and west, the arm of the couple is equal to the full length l of the needle, whence the moment is $m \times H \times l$. This moment decreases as the needle moves round towards zero, or that position in which it is pointing north and south. The moment is then reduced to nothing, M becoming $m \times H \times 0$, because the length of the arm is nothing; consequently, the needle remains at rest.

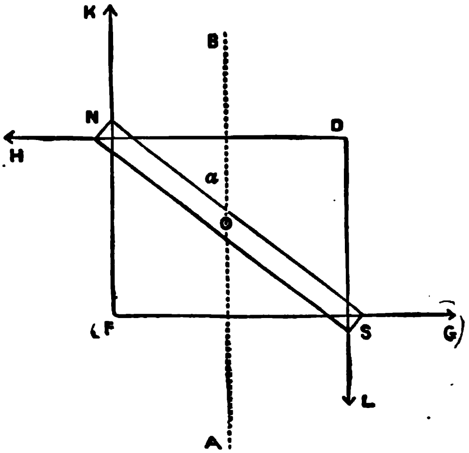
FIG. 51.



Now, we can cause any current, the strength of which we may desire to measure, to develop a field of strength f, at right angles to the earth's directive force – that is to say, we can cause the current to travel north and south, and by so doing deflect a magnetic needle from its zero position. Then the new force acting on each end of the needle will be $m \times f$, where m is the strength of the magnet pole; and, the length of the arm being calculated as before, the moment will be $m \times f$ multiplied by that arm. Manifestly, the needle will come to rest when the moment of the couple due to the current is equal to that due to the earth.

Let the needle N S (fig. 52) be so deflected by a current, and make an angle, N O D, called the angle of deflection, with the magnetic meridian A B. This angle N O B is, of course, equal to the angle N S D. Let this angle be called $a°$, and let f be the strength of the field due to the current, the direction of the action of which is indicated by the arrows D H and F G. D S is then the perpendicular distance between these directions, whence the moment of the couple due to the current is $m \times f \times$ D S.

FIG. 52.



By similar reasoning it will be seen that the moment of the couple due to the earth is $m \times$ H $\times$ N D. Now, if the needle has assumed a state of rest, showing that the moments of these two couples are equal, it follows, as a matter of course, that

$$m \times f \times \text{D S} = m \times \text{H} \times \text{N D},$$

and (by cancelling and dividing)

$$f = \text{H} \frac{\text{N D}}{\text{D S}}.$$

The ratio $\frac{\text{N D}}{\text{D S}}$ is called the tangent of the angle N S D, which, again, is equal to the angle of deflection $a°$ that is to say,

$$f = \text{H} \tan a°.$$

This strength of field, f, is proportional to the current producing it; therefore the current, C_1, is likewise proportional to H tan $a°$.

And this will be true of all currents and all deflections, so that if we let a second current, C_2, cause the needle to be deflected through the angle $b°$, then C_2 must be proportional to H tan $b°$.

Consequently, $C_1 : C_2 :: H \tan a^\circ : H \tan b^\circ$,

that is, $C_1 : C_2 :: \tan a^\circ : \tan b^\circ$,

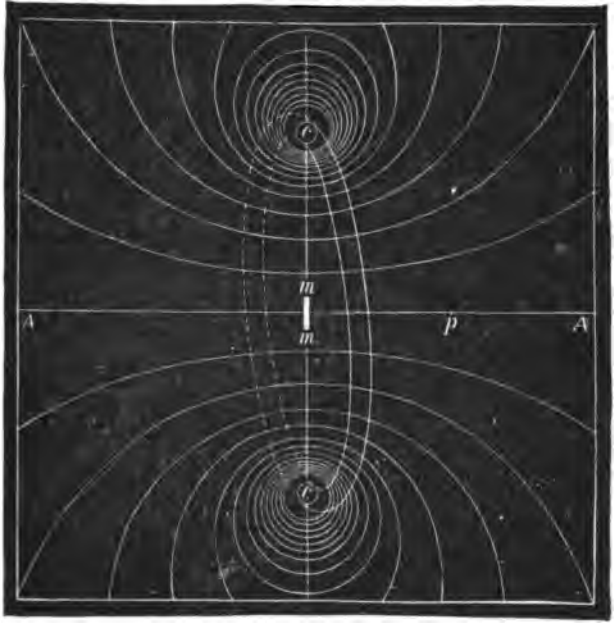
or the two currents are directly proportional to the tangents of the angles through which they deflect the needle. By referring to a table such as is here given, we can find the numerical value of the tangents of these or other angles, and so can easily compare the strength of the currents.

TABLE OF NATURAL SINES AND TANGENTS.

Deg.	Sine	Tangent	Deg.	Sine	Tangent	Deg.	Sine	Tangent
1	·017	·017	31	·515	·601	61	·874	1·80
2	·035	·035	32	·530	·625	62	·883	1·88
3	·052	·052	33	·544	·649	63	·891	1·96
4	·070	·070	34	·559	·674	64	·899	2·05
5	·087	·087	35	·573	·700	65	·906	2·14
6	·104	·105	36	·588	·726	66	·913	2·24
7	·122	·123	37	·602	·753	67	·920	2·35
8	·139	·140	38	·615	·781	68	·927	2·47
9	·156	·158	39	·629	·810	69	·933	2·60
10	·173	·176	40	·643	·839	70	·939	2·75
11	·191	·194	41	·656	·869	71	·945	2·90
12	·208	·212	42	·669	·900	72	·951	3·08
13	·225	·231	43	·682	·932	73	·956	3·27
14	·242	·249	44	·694	·965	74	·961	3·49
15	·259	·268	45	·707	·000	75	·966	3·73
16	·275	·287	46	·719	1·03	76	·970	4·01
17	·292	·306	47	·731	1·07	77	·974	4·33
18	·309	·325	48	·743	1·11	78	·978	4·70
19	·325	·344	49	·755	1·15	79	·981	5·14
20	·342	·364	50	·766	1·19	80	·985	5·67
21	·358	·384	51	·777	1·23	81	·987	6·31
22	·374	·404	52	·788	1·28	82	·990	7·11
23	·391	·424	53	·798	1·33	83	·992	8·14
24	·407	·445	54	·809	1·37	84	·994	9·51
25	·422	·466	55	·819	1·43	85	·996	11·43
26	·438	·488	56	·829	1·48	86	·997	14·30
27	·454	·509	57	·838	1·54	87	·998	19·08
28	·469	·532	58	·848	1·60	88	·999	28·63
29	·485	·554	59	·857	1·66	89	·999	57·29
30	·500	·577	60	·866	1·73	90	1·000	Infinite

An instrument which will enable us to make these comparisons is called a tangent galvanometer; but in order to obtain accurate results one important point must be carefully attended to in designing the instrument, for the foregoing proof only holds good when the two forces forming a pair act parallel to each other in any and every position of the needle. This means, in short, that the field due to the earth, and that due to the current, must be uniform throughout the entire space in which the needle can be moved. Fortunately, we can, by using a very short needle, make this space proportionally small, and thereby render the problem easier. The earth's field, as has been already stated, is uniform, but that due to a current is far from uniform, more particularly in the immediate vicinity of the wire, consequent on the very decided curvature of the lines of force. However, as we get farther away from the wire, these lines approximate more and more to straight lines, and if we bend the wire into a ring of large diameter we shall find a small space at its centre where the lines of force are, to all intents and purposes, straight and parallel. In fig. 53 is shown a horizontal view of the ring and of the distribution of the lines of force in the field. The two ellipses repre-

FIG. 53.



sent the ring itself, of which *c c* are the horizontal sections and A A the axis. The magnetic needle is indicated by *m m*. If we, therefore, suspend the small needle here, the necessary conditions for a tangent galvanometer are satisfied; the needle being too short to permit of its poles being moved into an irregular or variable part of the field.

With a ring 6 inches in diameter we can, in fact, use a needle three-quarters of an inch in length without the risk of introducing any sensible error.

Such a ring of wire, then, with a needle suspended at its centre, will serve to compare and measure current strength according to the law which we have just stated, i.e. each current will be proportional to the tangent of the angle through which it can deflect the needle. When made in a practical form, the tangent galvanometer is one of the most useful pieces of apparatus at our command.

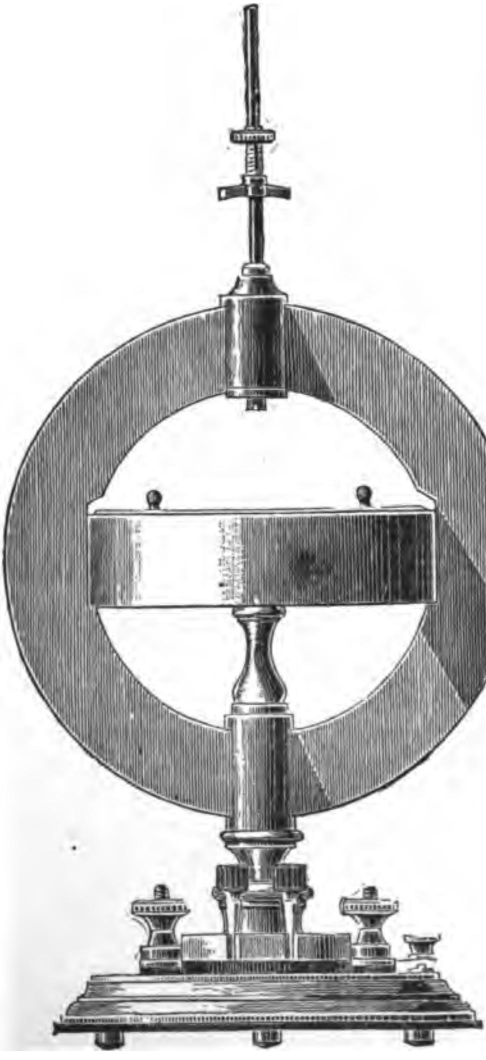
It is important to notice here that a variation in the strength of the magnetic needle will introduce no error in the readings; for if, for instance, a needle loses its magnetisation or becomes weak, it is acted upon more feebly both by the earth and the current, and in the same proportion, so that the weakened effect of the earth's field is balanced by the equally weakened effect of the current's field.

Proceeding now to a consideration of the laws governing the construction of the instrument, it is essential to remember that the force with which a current deflects the needle is proportional to the length of the wire, and inversely proportional to the square of its distance from the needle. But if we increase the size of the coil, we not only increase the distance from the wire to the needle, but also increase the length of the wire in exact proportion to the increase of the radius. Now the former reduces and the latter increases the effect; the joint result is that the force with which the needle is deflected varies inversely as the radius of the coil for the same current.

If, therefore, we use one coil of 3 inches radius, and another of 6 inches radius, the deflection will be the same when the current in the larger coil is double that in the smaller.

With, however, a single turn of wire 6 inches in diameter, only

FIG. 54.



comparatively strong currents can affect the needle, and, as we have seen, we are prohibited from reducing this diameter for the purpose of obtaining a sensible deflection with comparatively weak currents. But this difficulty can be easily overcome for we can increase the length of the wire, without increasing the distance from the needle, by the simple device of coiling it round the needle a number of times. Since the effect on the needle varies directly as the length of a wire, and the length of a wire of two turns is double that of one turn, the effect on the needle is doubled also; in other words, the effect on the needle varies directly as the number of turns of wire in the coil. It follows that, with equal currents, a 6-inch coil of one turn will give the same deflection as a 12-inch coil of two turns.

It must be remembered, however, that if the number of convolutions is increased to any great extent the resistance becomes considerable, and the very act of inserting the galvanometer in a circuit may decrease the current we desire to measure.

Bearing all these points in mind, we will now consider a really practical instrument for the measurement of current strength, selecting for description the pattern which is undoubtedly the best yet constructed—viz. the Post-Office tangent galvanometer. A general view of the instrument is shown in fig. 54.

The casing is of brass. The mean diameter of the coil is $6\frac{1}{2}$ inches; the width of the channel in the brass ring which contains the wire is $\frac{3}{16}$ inch, and its depth $\frac{3}{8}$ inch. The length of the needle, which is carefully pivoted with agate on an iridium point, is $\frac{3}{4}$ inch.

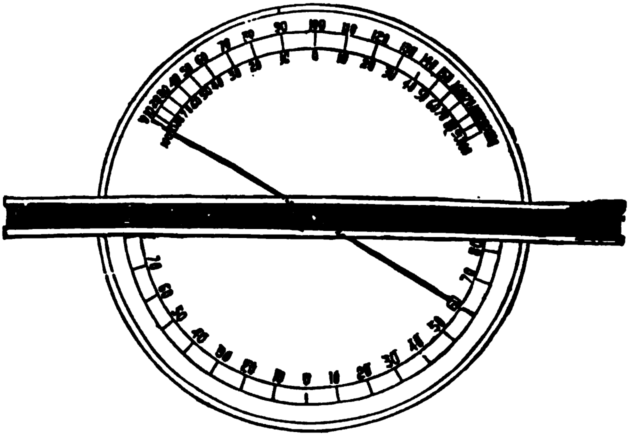
As this needle is too short to indicate its own deflections, it carries a light pointer of gilt copper wire, about 5 inches in length, fastened to it at right angles. This pointer moves over an engraved circular scale plate, one half of which is divided in degrees, the other half into divisions corresponding to the tangents of those degrees, as shown in fig. 55.

It may be of service to some if we refer here to the manner in which this tangent scale is constructed.

Let the quadrant O L (fig. 56), represent a portion of the circle along which the scale is to be marked, and let C O be the radius along which the index needle is to point when at rest and when no current is circulating through the coil of the instrument. Then draw the tangent line, O D, that is to say, a line at right angles to

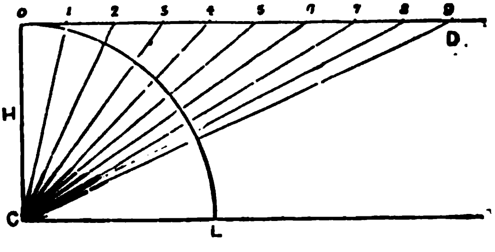
O C, meeting it in O. Then mark off along O D any number of equal divisions, and project lines from those points or divisions to C, the centre of the circle, intersecting the quadrant at various

FIG. 55.



places. These points of intersection will then correspond to the equal divisions along O D, and will be proportional to the tangents of the various angles which would be measured at those intersections.

FIG. 56.

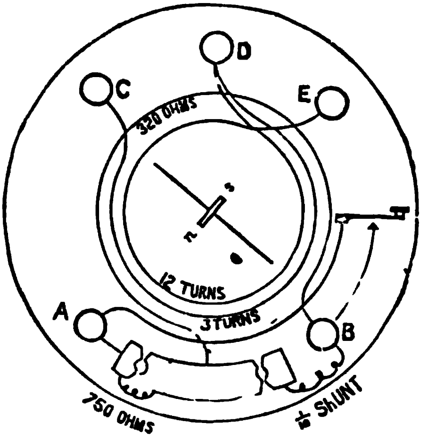


This device saves the operator the trouble of ascertaining from a table the 'tangent' equivalents to the various deflections and then calculating their relative values.

A piece of looking-glass is placed under the scale-plate and is exposed at two circular slots in the plate, so that in taking a reading the observer may let the pointer cover its own reflection, when he will be assured that he is looking vertically down upon it, avoiding thereby any error due to parallax—that is to say, any inaccuracy in reading caused by looking at the pointer sideways. A lever, operated by a small switch extending through the box which carries the needle and scales, is provided for lifting the needle off its pivot when not in use. There is also a small adjustable magnet which slides on a brass rod over the needle, and is used for varying the sensibility of the instrument. This may appear to be a step backwards from the beautifully simple thesis upon which the instrument is constructed. If there were no good reason for introducing this 'controlling' magnet to vary the sensibility of the instrument, the wisdom of its introduction would be questionable. But it must be remembered that there are several hundreds of these instruments in use throughout the country, and if it is known that a reading of twenty-five divisions corresponds in every case to a current of 1 milliampere, the direct value of any other reading can be confidently estimated. The controlling magnet, when placed with its S. pole over the N. pole of the needle, assists the directive force of the earth's magnetism and reduces the sensibility, and *vice versâ*. Either effect may be varied by sliding the magnet up or down the rod. For instance, the needle will move from zero with the weakest current when the magnet is placed at the bottom of the rod with its poles opposing the earth's magnetism.

A reference to fig. 57 will make the conception of the electrical portion of the instrument easier. There are three separate coils of wire in the brass ring, or bobbin, the ends of each being brought down through the hollow pillar and connected under the base of the instrument to their respective terminal screws, as shown in plan on the figure. Between the terminals C and D is a coil consisting of three turns of thick wire; between D and E are twelve turns of similar wire, wound in the opposite direction. If the current be sent from C to E, we get nine turns acting on the needle, for three of the twelve turns are neutralised by the three in the opposite direction between C and D. The resistance of these coils is negligibly low, so that we are able to get the effect from three, nine, or twelve turns without varying the strength of the current. The other coil consists of a great many turns of fine silk-covered wire. Its resistance is exactly 320 ohms. One end of it is joined to terminal B, and the other end to the middle brass block. By inserting a brass plug in the

FIG. 57.



left-hand hole, the end of the coil attached to the middle block is connected to terminal A direct. If, however, this plug is removed, the current in travelling, say, from B, has to pass through an additional resistance coil of 750 ohms (which is fixed under the base of the instrument) before it reaches terminal A. Under these circumstances the total resistance between A and B is 1,070 ohms. Suppose now a single Daniell cell, whose resistance is comparatively low, to be joined to terminals A and B. By Ohm's law the current is equal to $\frac{1\cdot07 \text{ volts}}{1{,}070 \text{ ohms}}$, or ·001 ampere—that is, 1 milliampere.

These resistances are, in fact, calculated for use with a single Daniell cell as a standard. We can always immediately produce a deflection which we know to be that due to 1 milliampere of current, and find the value of any other current by observing its deflection under similar conditions. A small key is fixed on the base of the instrument; when depressed it connects A and B as will be seen from fig. 57, or, in the usual language, it short-circuits the coils. It is used for checking the oscillations of the needle and bringing it quickly to rest.

It is sometimes required to measure a current so strong that the deflection is inconveniently high. In this case a part of the current may be 'shunted,' or provided with an alternative path, or, more correctly speaking, a by-path, so that only a portion of the current shall go through the galvanometer, the rest going through the shunt. It is necessary, however, to know exactly what fraction of the total current is passing through the instrument and what through the shunt. If we join the ends of the coil by a shunt equal to it in resistance, then the current will divide equally between the two paths, and only half of the total current will be measured. If the resistance of the shunt be $\frac{1}{9}$ that of the galvanometer, then $\frac{9}{10}$ of the current will pass through the shunt and the other tenth through the galvanometer. In this case, therefore, the total current will be ten times that measured by the deflection of the needle.

The instrument we are now describing is provided with such a shunt; its resistance is $\frac{320}{9}$ ohms, and fig. 57 clearly shows how it may be brought into play by inserting a plug in the right-hand hole, thus connecting together the middle and right-hand blocks. Suppose, when the adjustment is such that 1 milliampere gives twenty-seven tangent divisions, that we insert this tenth shunt, and then with a current of unknown strength obtain eighty-one divisions. The current flowing round the galvanometer is manifestly 3 milliamperes, but this is only $\frac{1}{10}$ of the whole, consequently the total current is 30 milliamperes.

In order to reduce the current flowing through a galvanometer to any fraction of its full value, say, to $\frac{1}{n}$, the resistance of the shunt necessary to produce that result must be $\frac{1}{n-1}$ that of the galvanometer. A moment's reflection, however, will make it evident that the introduction of a shunt reduces the resistance of the circuit, and may, therefore, cause a considerable and material increase in the current strength. Where this increase of strength is appreciable, the introduction of extra resistance sufficient to compensate for the fall caused by the shunting becomes necessary, the problem being to ascertain exactly how much compensating resistance is required. By the laws of the joint resistance of two parallel wires, explained in Chapter II, the joint resistance of the galvanometer, G, and the shunt, S, will be equal to $\frac{GS}{G+S}$. Now, the resistance of S has just been shown to be $\frac{1}{n-1}$ part of G, or $\frac{G}{n-1}$, that is, if only a tenth of the current is to pass through the galvanometer, the shunt resistance should be $\frac{1}{10-1}$ part of the galvanometer resistance G. That is to say, $S = \frac{G}{n-1}$, and inserting this value we get—

$$\frac{GS}{G+S} = \frac{G\,\frac{G}{n-1}}{G + \frac{G}{n-1}},$$

which is equal to $\frac{G}{n}$.

So that the joint resistance of a galvanometer coil of 320 ohms and its tenth shunt will be $\frac{G}{n} = \frac{320}{10} = 32$, whence it follows that the reduction in resistance due to the use of the shunt amounts to $G - \frac{G}{n}$, or $320 - 32 = 288$. 288 ohms is, therefore, in this case the resistance that it would become necessary to introduce in order to restore the resistance ot the circuit to the same value that it had prior to the introduction of the shunt. And, generally, it may be said that the introduction of a shunt reduces the resistance of the circuit to the extent of $\frac{n-1}{n}$ G, and that amount of resistance will need to be inserted to re-establish the conditions of the circuit. In short, this compensating resistance is equal to the difference between the resistance of the galvanometer alone and of the galvanometer shunted.

When great accuracy is desired, all the readings on the tangent galvanometer should be taken with the needle deflected as nearly as possible through an angle of 45°. The reason for this is, that any given variation in the strength of the current will produce a greater effect on the needle when it is in that position than when in any other, or, in other words, the sensitiveness of the instrument is then at its maximum. For instance, if, when the needle were deflected through 45°, an increase of the current by one-twentieth gave an increase of half a degree in the deflection, a similar increase in the current when the needle stood at 10° or 80° would not be indicated at all, or rather, the deviation would not be discernible.

Every galvanometer has a definite *angle of maximum sensitiveness*, or such an angle of deflection that with a small accretion of current there will be a larger divergence than when the needle is at any other point on the scale. The mathematical demonstration of the existence of this angle would be somewhat beside the scope of this work, but we may repeat that for every tangent galvanometer the angle of maximum sensitiveness is 45°. We should always endeavour, therefore, when using this instrument to get the deflection as near 45° as possible, or when comparing two currents get the deflections at equal distances on either side of this point. It has already been pointed out that it is very convenient, we would say more, it is necessary, in practice to be able to determine immediately the value in amperes or milliamperes, to which some particular deflection of the needle corresponds, and it will be remembered that with a Daniell cell as a standard a current of 1 milliampere may be immediately produced.

The Latimer-Clark cell is less liable to variation and is much more trustworthy than the Daniell when used with a very high external resistance. Although, in order to obtain the most accurate results, this cell should only be employed in those tests where it is not allowed to send any current at all, its portability and the fact that it is always ready and in good order are such important advantages that it is frequently used in such a test as the preceding, under conditions which, perhaps, render it no more accurate than the Daniell. Its resistance, which is as a rule considerable, should be known, and, by using an extra coil, the resistance in circuit can then be made 1,435 ohms. The electromotive force of one of these cells being 1·435 volt, it follows that through the resistance of 1,435 ohms it will yield a current of exactly 1 milliampere, or,

$$\frac{1{\cdot}435}{1{,}435} = {\cdot}001 \text{ ampere.}$$

The foregoing applies to a galvanometer with a tangent scale constructed so that its zero point is in the centre, as is the case with the *inner* scale on the tangent divisions side in fig. 55. But it will be seen that in this figure there is an outer scale also of tangent divisions, but with the zero point at the extreme left-hand, where the pointer is shown resting. This outer scale is known as the 'skew scale,' from the position of the needle when at zero, and its great advantage lies in the fact that the range of measurement is double that of the ordinary scale. For a comparatively high reading, also, the deflection can be read with greater ease as the pointer is not in the part of the scale where the divisions are close together. It is true that a small deflection cannot easily be read, but the ordinary scale can be employed for this if necessary.

Unfortunately, the tangent galvanometer is but little suited for the measurement of very powerful currents such as those generally employed in electric lighting. We must, therefore, now direct attention to an instrument which will answer this purpose, and one which is beautifully simple in its conception, and at the same time remarkably accurate and free from error. It is based upon the simple experiment mentioned at the commencement of this chapter, viz., the attraction or repulsion which takes place between two wires carrying currents. It may now be stated that the force of this attraction or repulsion is readily measurable, being, in fact, proportional to the strength of one current multiplied by the strength of the other, provided that the distance between the two wires remains constant. If we suppose the currents in each of the wires to be exactly equal, say 2 amperes, then the force may be represented by the number $2 \times 2 = 4$. Now if we double the current strength in each wire, the force of attraction or repulsion will be $4 \times 4 = 16$; in other words, when the current strength in each is doubled, the force between them is quadrupled. Similarly, if we treble the current in each wire, or make it 6 amperes, then the mutual force will be $6 \times 6 = 36$, or nine times as great as when the current was 2 amperes. We therefore see that the force of attraction or repulsion between two wires carrying equal currents varies as the square of the current strength. It will be apparent that the simplest method of obtaining equal currents in each wire is to join them in series, and send the same current through both of them in succession. Then, if any number of currents be sent through them, the force of the action between the wires will be proportional to the square of the strength of the current in each case, whence it may be reasoned that if these forces can be measured or compared, the currents producing them can also be estimated; for as the force varies as the square of the current, the current will vary as the square root of the force exerted by it.

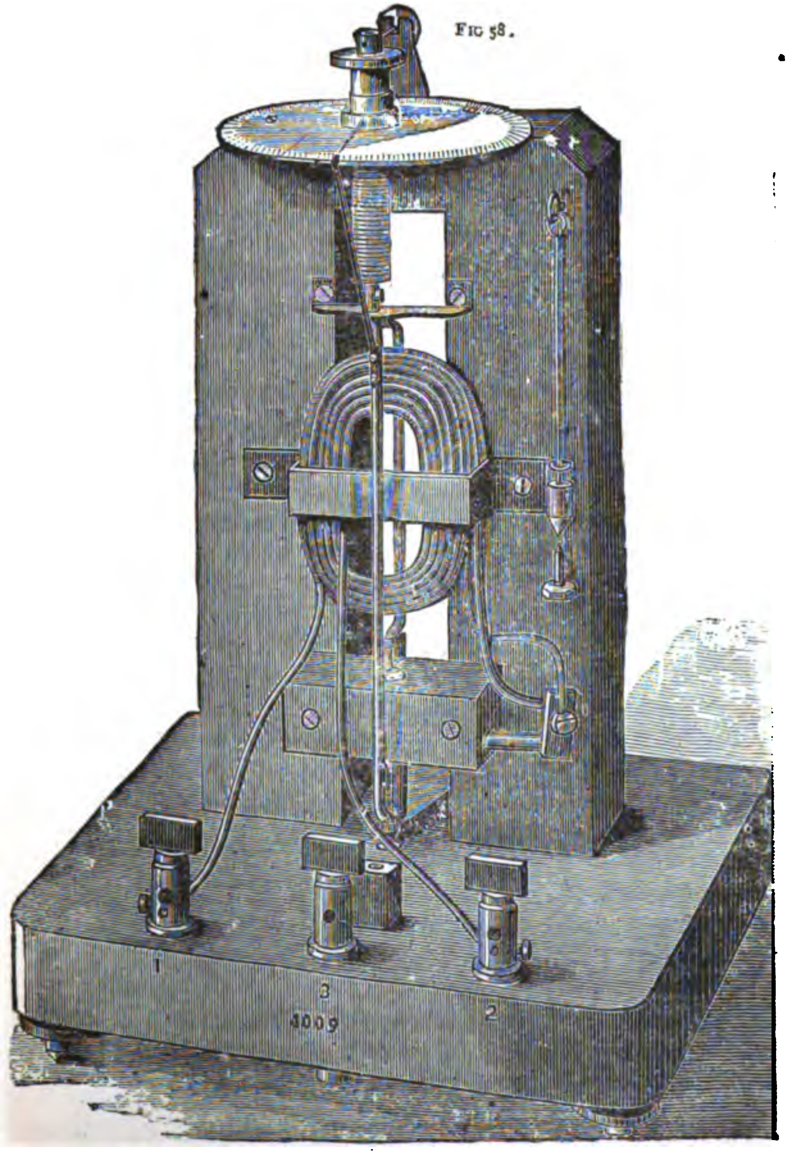
In constructing an instrument on this principle, it is necessary, therefore, to have some means of accurately measuring the force exerted, and also to ensure that the distance between the wires remains exactly the same during all the comparisons.

The *Siemens dynamometer* fulfils all these conditions to the letter. A general view of this instrument is given in fig. 58, fig. 59 showing the manner in which the principle is applied. The two wires (or coils) are rectangular in shape. One of them, A B C D, is rigidly fixed to a vertical support, while the other, E F G H, which is sufficiently large to embrace the fixed wire, when the plane of the one is at right angles to that of the other, is suspended by a stout silk thread.

In the actual instrument this movable coil consists of a single turn of thick wire; and in order that the current may be passed through it, without in any way impeding or interfering with its freedom of motion, its two ends, G and H, are brought round and bent down into mercury cups placed vertically one over the other, so that the two ends and the point of suspension, K, are in the same vertical line.

Connection with the mercury is made by a wire passing in at the bottom of the cup. The arrows in fig. 59 show the direction of the current in the various parts of the circuit, when a current is sent through both coils in series, and it is easy to see that each vertical limb of the movable coil will be urged, by repulsion on one side and attraction on the other, to set itself in the same

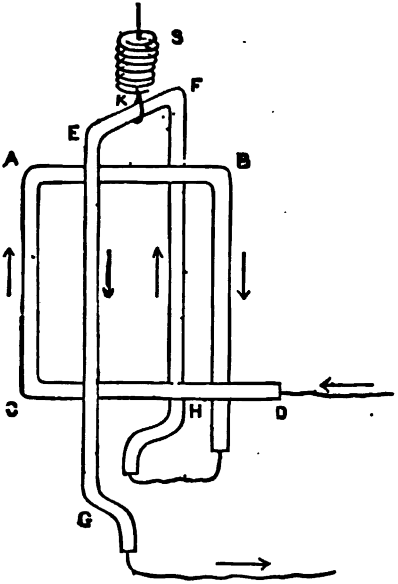
FIG 58.



plane as the fixed coil. But it has already been said that it is essential that the coils should remain or be brought back into the same relative positions when the force between them is measured. In the Siemens dynamometer the position selected is with the planes of the two coils at right angles; and the force measured is that force which is necessary to keep the movable coil in this position against the action of the current.

This antagonistic force is applied by means of a spiral spring, S,[1] the lower end of which is rigidly fixed to the rectangle E F G H; while its upper end is fixed to a mill-headed screw, which can be turned round, torsion being thereby applied to the spiral spring. A pointer is attached to the screw-head and moves with it, and travelling over a graduated scale, divided usually into 400 equal divisions instead of 360 degrees, indicates the amount of torsion applied to the spiral spring in bringing the coil E F G H back to the zero position, against the opposing force due to the current circulating in the coils. It is a simple and well-known law that the force of torsion is proportional to the angle of torsion, and as the angle through which the screw is turned in order to keep the movable rectangle at zero is an exact measure of the torsion applied, the force necessary to the production of that angle must be proportional to the force acting between the two coils, and due to the current circulating in them. This latter force varies, as we have seen, as the square of the current strength, so that, therefore, the current is proportional to the square root of the angle of torsion. The movable coil also carries a pointer, the end of which just over-

FIG. 59.



laps the scale-card and plays between two pins about half an inch apart. When it points to zero, the two coils are accurately at right angles one to the other.

The instrument has usually two separate and distinct fixed coils; one consisting of a few turns of thick wire, and the other of a larger number of turns of thinner wire. The object of this arrangement is to facilitate the measuring of currents differing very considerably in strength, and so to increase the available range of the instrument. One end of the thin-wire coil is joined to the left-hand terminal screw (fig. 58), and one end of the thick-wire coil to the right-hand screw. The other two ends are connected to the upper mercury cup, while the lower cup is joined to the middle terminal screw.

For a very strong current, then, the centre and right-hand terminals, giving the thick-wire and movable coils, should be used; while for a weaker one, the centre and left-hand terminals, between which are the thin-wire and movable coils, should be employed

On account of the operation of the law of the square, a more accurate reading can be obtained in the higher part of the scale than in the lower, and it is therefore, where possible, more advantageous to use the thin-wire coil for such currents as would give only a low reading with the thick-wire coil.

Three levelling screws and a level are provided, it being absolutely essential that the coils should be exactly perpendicular. The movable rectangle can be raised or lowered by means of the thread which is attached to a screw at the top of the instrument, until it moves quite freely and makes good contact with the mercury. It is difficult to replace this silk thread quickly, and this constitutes a weak point in the instrument, for an inexperienced operator frequently commences his experiment by breaking it.

The instrument requires calibration, that is to say, it is necessary to find out to what current strength a certain amount of torsion is equivalent, before any unknown current can be measured in amperes. This calibration may be effected by deflecting the rectangle by a current of known strength, and then by turning the milled-head attached to the upper end of the spiral spring, applying just sufficient torsion to restore the pointer attached to the rectangle to the zero position. Suppose the current to be one ampere and the torsion applied 16 divisions. Then if a current of unknown strength be sent through the same coil, and it is necessary to apply 64 divisions of torsion to bring the rectangle back to zero, the latter current will be 2 amperes strength; for

$$c_1 : c_2 :: \sqrt{16} : \sqrt{64},$$

that is as 4 is to 8, or as 1 is to 2.

In practice such calculations would be exceedingly inconvenient; the makers, therefore, calibrate the instrument or determine what strength of current corresponds to the various angles of torsion, both for the thin- and thick-wire coils. These results are tabulated in a convenient form and supplied with the instrument.

On referring to fig. 59 it will be observed that, if the current is reversed, the rectangle will still be deflected in the same direction, because, the direction of the current in *all* the sections being altered, attraction or repulsion will take place between the same limbs as before.

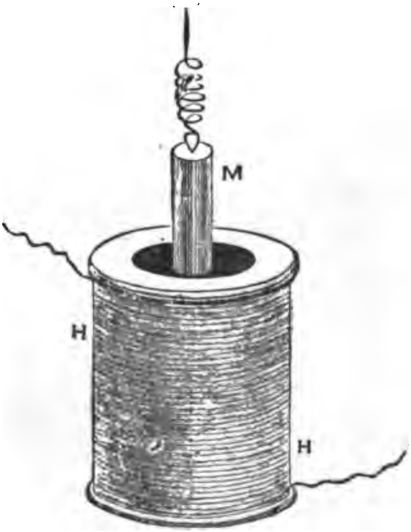
The instrument can therefore be used to compare either positive or negative direct currents, or even alternating currents —*i.e.*, those whose direction is rapidly reversed. The pointer attached to the screw-head should always stand at zero when the instrument is not in use, otherwise the spiral spring will take up a *set* and will not bring the rectangle to zero when the pointer is brought there. The spring will, however, gradually recover from any such set if it be not excessive.

The Siemens dynamometer is a very accurate instrument when used with ordinary care, but every measurement occupies a certain amount of time, for in every case the rectangle has to be brought back exactly to zero, the amount of torsion noted, and then the table referred to, to ascertain the current strength to which this torsion corresponds. It is evident that an instrument which immediately indicates in amperes the strength of the current flowing is far more convenient to use, although, unfortunately, a *direct-reading* instrument has not yet been designed which may be relied upon for any length of time to be as accurate as the Siemens dynamometer.

For portability and the rapidity with which measurements may be taken, Ayrton and Perry's ammeter (or ampere-meter) stands in the front rank.

It is based upon the fact, that a piece of soft iron placed in a magnetic field which is not uniform, will be urged from a comparatively weak into the strongest part of the field. One way of viewing the action is to consider the iron, M (fig. 60), as a magnet for the time being, and then if the field be generated by a current circulating round a helix of wire, H H, and the iron is placed just outside the helix, it will be sucked down until it reaches the middle of the helix, which is the strongest part of the field. Now, this action will be proportional to the product of the strength of the field and the strength of the temporary magnet; as the latter varies with the strength of the field, but not according to any regular law, the readings will not be proportional to the current strength unless by some means the strength of this temporary magnet is kept constant. Experiment shows that although the magnetic lines of force pass readily through a piece of iron when there are very few lines already there, yet, when a great many are present, any further addition to their number becomes very difficult. When in this latter condition the iron is said to be 'saturated.' A piece of *very thin* soft iron tubing becomes saturated even in a weak field, that is, in a field traversed by but few lines of force; so that beyond a certain stage, although the strength of the field is increased, the number of lines of force passing through the iron tubing, that is, its strength considered as a magnet, remains practically the same. Therefore, if we use a

FIG. 60.

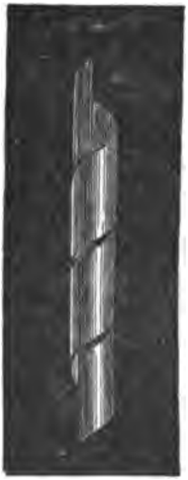


very thin tube of soft iron, the force with which it is sucked into the helix will, for all fields above a certain strength, depend simply upon the strength of the field and will be proportional thereto, and consequently, also proportional to the strength of the current producing the field.

Except for weak currents, then, we may estimate the strength of a current by measuring the pull on such a thin tube of iron placed partly inside a helix. It must not be placed exactly in the middle of the coil, as that, being the strongest part of the field, is the position of rest for the iron.

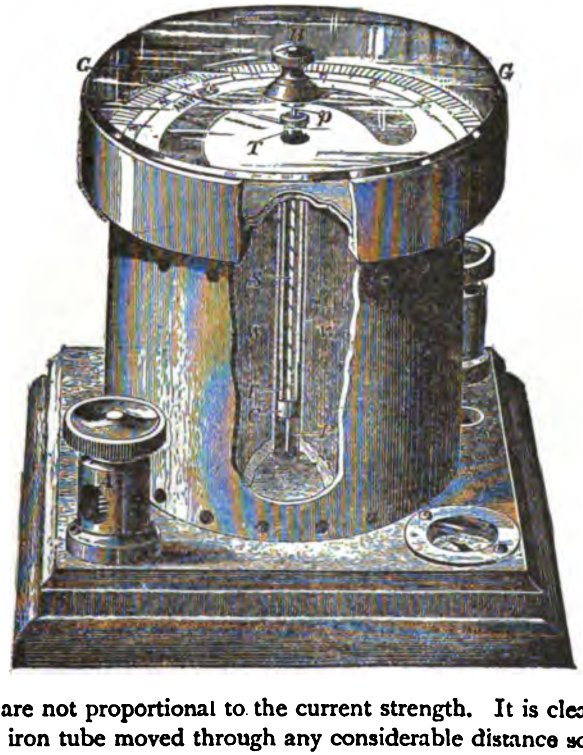
In the instrument under consideration the method of measuring the pull is unique. It depends upon a peculiar property possessed by a flat spiral spring shaped like a curled-up shaving, as illustrated in fig. 61. If such a spring be stretched while one end of it is fixed, the other end will rotate, and the angle of rotation will be exactly proportional to the amount of stretching, the angle being considerable for a small extension of the spring. A reference to fig. 62 will show how these principles are combined in the actual instrument.

FIG. 61.



The helix fills the space marked W W, and is composed of stout wire offering little resistance, so that its introduction into a circuit does not diminish the current flowing therein. T is the thin tube of soft iron which is sucked down more or less by the current, its lateral movement being prevented by two small brass pins, P and *p*. The former is fixed to a small piece of brass, C, which is fastened to the bottom of the soft iron tube. The spiral spring is placed inside this tube, its lower end being rigidly fixed to C and its upper end to the brass pin *p*. As *p* is also rigidly connected to the screw-head, H, the upper end of the spring cannot rotate, therefore when the tube T is sucked down the lower end of the spring rotates, carrying with it the tube. The upper end of the tube which projects out of the coil carries a pointer which moves over a graduated scale, and so indicates the angle of rotation, the usual horizontal mirror being provided to avoid parallax. The scale is divided into equal divisions representing amperes and fractions of an ampere, but as the iron does not become saturated until the current has attained a certain strength, the first portion of the scale is never used, and is, in fact, not graduated, for, as has been explained, the indications at this stage are not proportional to the current strength. It is clear that if the iron tube moved through any considerable distance so as to get into a part of the field of different strength, the readings would not be proportional; but it will be remembered that the peculiarity of the spring is that the angle of rotation is great for a very small extension in length, consequently the pointer traverses the whole

FIG. 62.



range without the distance through which the iron moves being sufficient to cause inaccuracy. The instrument is calibrated by the maker, similar scale-cards having equal divisions being used for all instruments of the same range, and the adjustment effected by shifting a small auxiliary coil. When a current is sent through the instrument the pointer indicates at once the number of amperes of current flowing, thus avoiding calculation or reference to a table Occasionally, however, comparison should be made with some reliable standard, such as a Siemens dynamometer, for the instrument is liable to variation after continued use.

The pointer moves in the same direction, no matter in what direction the current is sent through the coils, because the magnetism of the iron tube is also reversed. There is a possibility here of an error being caused by the retentivity of the iron, but as it is so thin and soft its magnetism is readily completely reversed, and no error is introduced from this cause. In order to indicate the direction of the current a small magnetic needle is usually fitted in the base-board, and its blue-coloured end points towards the terminal screw at which the current enters. The pointer can be adjusted to zero by turning the milled head H. The coils and tube are surrounded by an iron casing, which, as will be explained hereafter, prevents any external currents or magnets affecting the tube and so causing inaccuracy in the readings.

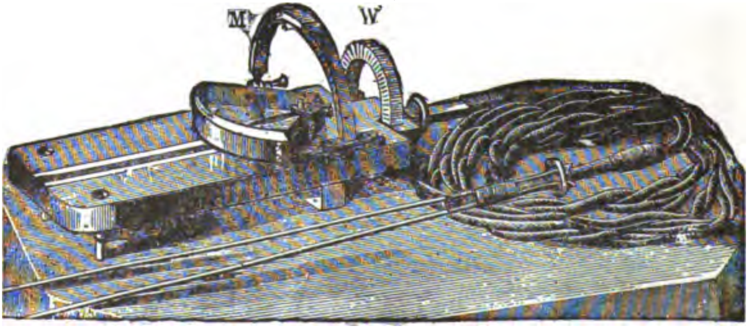


FIG. 63.

Sir William Thomson has designed several forms of current-measuring instruments, one of the best being that illustrated in fig. 63, and known as the graded ammeter. It may be regarded as a form of tangent galvanometer, the coil-ring, W, consisting of one or more turns of stout copper wire or ribbon. The magnetic needle is very small and delicately balanced, and carries a long light pointer which travels over a scale in the bottom of the sector-shaped case or box. A controlling magnet, M, semicircular in shape, is fixed to this box, which slides in a V-groove in the base of the instrument. This magnet is somewhat powerful, sufficiently so, in fact, to overpower the effects of terrestrial magnetism, whence, the magnet moving with the needle, a practically constant field is maintained in any and every position in which the instrument may be placed.

When in the zero position the needle, coil, and magnet are in the same vertical plane. A scale is let into the base, along the edge of the groove, to facilitate the necessary calculations. The object aimed at in this method of construction is to provide an instrument capable of measuring current strengths of considerable difference, for it is evident that as the needle is withdrawn from the plane of the coil the effect of a given current upon it diminishes rapidly. The relative effect of a current upon the needle at different distances from the coil is proportional to the cube of the radius of the coil divided by the cube of the distance between the needle and the wire itself, that is, as $\frac{r^3}{b^3}$, where r is the mean radius and b the mean distance between the wire of the coil and the needle. This distance, b, is the hypotenuse of a right-angled triangle, whose base, a, is the axial distance between the needle and the plane of the coil, the perpendicular being the mean radius, r. These latter distances are more easily measured than b, and we may write the expression $\frac{r^3}{b^3}$ as $\frac{r^3}{(\sqrt{r^2 + a^2})^3}$.

Apparatus of this class cannot be used in the neighbourhood of dynamos or other large masses of moving iron, although it is often used in the laboratory. One great objection to it is the tedious calculation which has to be made for every reading. The controlling magnet is another source of trouble in consequence of its liability to vary. In order that the wires conveying the current shall not affect the reading, the main leads are connected to two long pieces of wire which are twisted together for a considerable distance as shown in the figure, so that each neutralises the tendency of the other.

We come now to the consideration of a class of ammeter, simple in construction and action, independent to a great extent of the proximity of extraneous electro-magnetic fields, and, being direct-reading instruments, they are exceedingly useful as dynamo-room indicators, telling the attendant at a glance whether or no his current is being maintained at its proper value. A number of these instruments depend upon the power of a coil alone, to raise a more or less weighty piece of iron against the force of gravity, while others have a solenoid and core to perform a similar operation. They all require to be calibrated, but, under the circumstances, that is not objectionable providing the calibration is correctly performed.

FIG. 64.

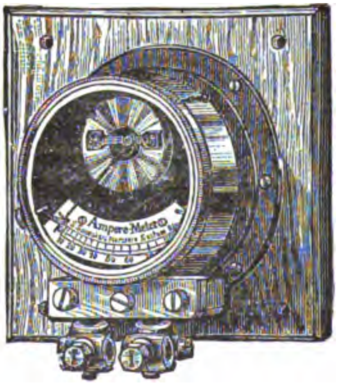
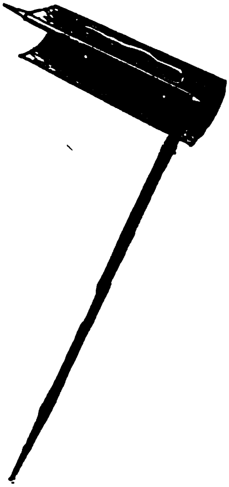


FIG. 65

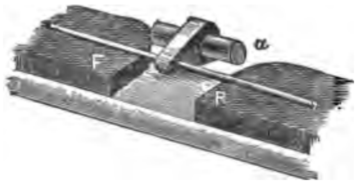


The first instrument of this class to which we will refer is that constructed by Schuckert. A general view of this ammeter is shown in fig. 64, and a view of the moving portion of it in fig. 65. It will be seen that the instrument is made to be fixed against a wall with its base in a vertical position, the working parts being protected by a circular metal case with a glass front. From the two terminal clamps below the instrument case, stout metal bands are led to the solenoid, which is placed with its axis horizontal, and consists of single copper casting, with helical saw-cuts, so as to lead the current a few times round the 'needle.' With such a solenoid, which is designed for very heavy currents, no insulating material is employed other than the air; but in the case of instruments constructed for the measurement of weaker currents, the solenoid is made of a number of turns of ordinary stout insulated wire. A light steel arbor or spindle is pivoted so as to lie parallel to, and a little to the left of, the axis of the coil. It has attached to it a thin curved plate of soft iron shaped as shown in fig. 65. This piece of iron is nearly equal in length to the arbor, and extends through the length of the solenoid. A light aluminium pointer is also fixed to the arbor at right angles, and the movable parts are so weighted that, in the absence of a current, the pointer is held in the zero position by the force of gravity

When a piece of iron is placed in a solenoid, but out of centre, the effect of a current is to bring the iron towards the centre. Therefore a current passing through the coil of the Schuckert instrument, in endeavouring to rotate the curved piece into the centre, raises it against the force of gravity, through a distance depending upon the strength of the current. The index attached to the arbor travels, therefore, over the scale which is placed behind it, and thus indicates the strength of the current passing through the instrument. As may be imagined, the divisions of the scale are unequal, but the scales of all instruments of the same range are exactly alike, the centre of gravity of the moving parts in each case being adjusted to suit the scale. The adjustment is made by bending a small piece of copper wire (see fig. 65) fixed at one end to the upper side of the arbor, but this operation is a matter of some difficulty when it is desired to reproduce a previous calibration. It is an interesting fact that the gross weight of the moving part is but $\frac{1}{30}$ of an ounce. The amount of friction is therefore very slight, and, there being very little in the instrument which is liable to vary with ordinary workshop usage, it is a useful and practical piece of apparatus.

The instrument known as the 'Gravity' ammeter is the invention of Mr. S. F. Evershed; it is manufactured by Messrs. W. T. Goolden & Co., and is for practical work an excellent and reliable measuring instrument.

FIG. 66.

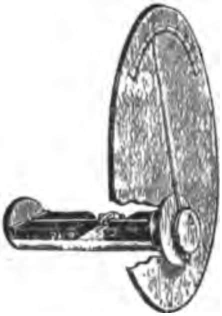


In this case also the magnetising coil is placed with its axis horizontal, and in the middle of it there lies a small cylindrical piece of soft iron, *a* (fig. 66), which is fixed, by means of a piece of brass, to a brass arbor, this arbor being pivoted at its extremities, and weighted so as to keep the small iron rod in the position shown. F and P are two small soft iron slabs, placed end to end, but just sufficiently far apart for the small iron rod, *a*, to swing freely between them.

The coil encircles these slabs, the arbor, and its attachments; and when a current passes through it, the lines of force gather up into the slabs, and pass lengthways along them, say from P to F, with the result that there is a very dense field just between their opposing ends.

In its normal position the small iron rod, *a*, lies almost outside this dense field, and we have seen that a piece of iron so situated is always urged from a weak part towards the strongest part of the field. Consequently, the iron piece, *a*, is drawn down against the restraining force of gravity which acts on the counterbalancing weight, and, as an increase in the current strength will add to the number of lines and to the force of attraction, the distance through which the iron piece is moved may be made to indicate the current strength. But the depression of the iron rod is not proportional to the increase in the current, consequently an ordinary degree scale, or any other equally divided scale, cannot be employed. Reverting for a moment to the construction of the instrument, it should be explained that, as shown in fig. 67, the two iron slabs (P, F, fig. 66) are fixed upon a stout brass strip, the remote end of which carries a brass disc forming one bearing for the arbor. At the near end of the strip is a larger disc, provided with a hole through which the spindle freely passes, having also fixed to it a smaller brass disc which forms the other bearing for the arbor. Between these two last-mentioned discs is a space sufficient for the pointer to swing freely throughout its range, and a small arm is also attached to the arbor, its end being tapped to fit a small nut which acts as the counterpoise, keeping the pointer at zero when no current is passing through the coils. The scale plate is vertical, so that the instrument, which in appearance resembles the voltmeter pictured in fig. 108, can be placed against a switchboard or wall, and its indications conveniently read. The calibration is carefully performed, and a separate scale is made for each instrument, instead of the instruments being altered to suit a common scale, with more or less accuracy, as is frequently done.

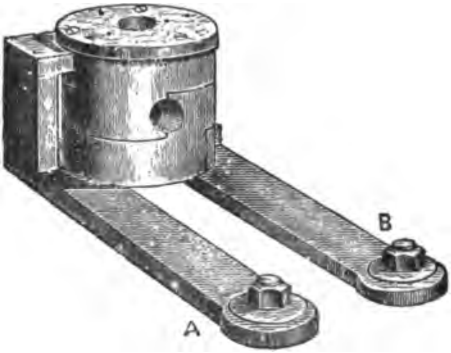
FIG. 67.



The ends of the iron slabs on the further side, as viewed in fig. 66, are curved slightly, and by altering this curvature, the force with which the iron rod is attracted in any given position can be varied. This enables the scale to be made to suit the work for which the ammeter is intended; for instance, an instrument whose range of measurement is from 20 to 200 amperes may be required for use on a circuit where the working current should never rise above 130 nor fall below 90 amperes, and in such a case it might be necessary to be able to measure exactly the value of the current between those limits, while the upper and lower parts of the scale would simply be used to indicate with certainty the fact of the current being either considerably too high or too low.

In such an ammeter the slabs would be so shaped that a given increase in the current strength would move the iron rod through a much greater distance when near the middle of its swing, than an equal increase would move it when it is near the zero position, or the extreme end of its journey. Consequently, on calibrating the instrument, we should obtain a scale open in the centre, and closed at the ends — that is to say, with much larger divisions in that part where the most accurate measurements are required to be made. On the other hand, the scale could, if required, be made open at the ends and closed in the middle, or, in fact, varied at any part to suit special requirements. For comparatively low currents the magnetising coil is wound with thick insulated copper wire, but for heavy currents, such as from 200 to 1,000 amperes, a specially constructed coil is employed. If the conductor has any appreciable resistance, such heavy currents develop a considerable amount of heat, and a cotton or silk insulating covering, besides impeding radiation, is very liable to get damaged. The best insulator is air, which is practically a perfect non-conductor, and indestructible, and has the advantage that it moves away when at all heated, its place being taken by colder air; the insulating material thus tends to keep the conductor cool instead of preventing the escape of heat, and only in very exceptional cases does the irregular dissipation of heat by the air currents introduce any error. Fig. 68 illustrates the magnetising coil employed to carry heavy currents. It consists of a massive cylindrical tubular casting of copper, the central hole being just large enough to admit the brass strip with the slabs, &c., shown in fig. 67.

FIG. 68.



It is divided by saw-cuts to form a 'coil.' The current, entering, say, by the straight connecting bar A, passes up the vertical strip to the top of the cylinder, and thence round the coil from back to front. It then passes down to the next convolution at the left of the drilled hole, where this particular saw-cut terminates, and thence round the coil again to the beginning of the third convolution, at the right of, and underneath, the drilled hole. After again going round the coil the current leaves by the bar B. It thus takes about 2½ complete turns round the coil, which, with a current of 300 amperes, would give 750 ampere turns.

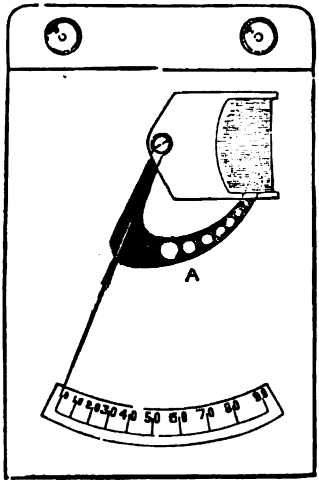
It will be evident that such a coil has very little resistance, and that therefore the power absorbed and the amount of heat developed in it will be correspondingly small. The instrument may consequently be kept continuously in circuit without any risk of damage or serious waste of energy. The bars by which connection is made are long and straight, to prevent the current in the leading wires affecting the 'needle,' for without these precautions a considerable error might, owing to the small number of convolutions, be introduced. In an instrument for measuring 1,000 amperes the 'coil' consists of a massive cylinder divided on one side by a radial saw-cut, with the straight connecting bars placed in a line with each other. In this case the current makes but ¾ of a turn round the needle, thus again giving, with 1,000 amperes, 750 ampere turns.

There is one possible source of error with instruments of this description due to the retentivity of the iron, but by exercising great care in the selection and treatment of the metal, this error has been practically eliminated. The iron, in fact, is not touched by a tool after it has been annealed, the film of oxide formed during that operation being simply dissolved by immersion in an acid. Perhaps the best way of testing for inaccuracy due to this cause is to take two sets of readings, one with ascending values of the current from zero to the maximum, and the other with corresponding descending values. Any retentivity of the iron would cause the latter set of readings to be higher than the former, but in these instruments the results are practically identical.

It is not so easy to accurately measure a current of several hundred amperes as it is to measure a few amperes or a fraction of an ampere, but all these ammeters are calibrated by having their full current passed through them, and its effect, as indicated by the pointer, carefully observed.

The required current strength is obtained by means of secondary batteries, which are charged in series and joined up in parallel for discharging, and in order to ensure greater accuracy a definite fraction only of the whole current is measured. For example, if it is desired to calibrate an ammeter which is capable of measuring from 40 to 400 amperes, it is joined up with the secondary battery, and a set of 100 rather stout iron wire resistances, these wires being all joined up in parallel, and placed so as to have equal facilities for cooling. A standard ammeter is joined up in circuit with one of these iron wire resistances, and a length of the iron wire equal in resistance to that of the ammeter is removed, so that this compound branch, formed of a portion of iron wire and the ammeter, is equal in resistance to each of the other 99 branches consisting only of iron wire. This standard ammeter is calibrated with extreme care, and as the main current divides equally among the 100 branches, the ammeter accurately measures one-hundredth of it, so that for the maximum current of 400 amperes it is only necessary to measure 4 amperes—a comparatively easy matter. For 1,000 amperes it would thus be necessary to measure only 10; but an ammeter designed to measure such a high current is conveniently calibrated by joining in series with it two 500-ampere meters which are themselves connected together in parallel.

FIG. 69.

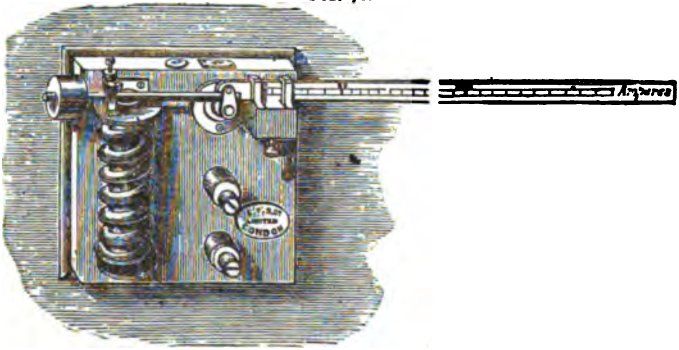


The absence of a portable instrument which will stand a little rough usage has hitherto restricted the measurement of alternating currents to such rather inconvenient instruments as the Siemens dynamometer, but it has recently been discovered that by slightly altering the proportions of the iron parts, these gravity ammeters answer admirably for measuring alternating currents, the difference in the readings caused by any variation in the rate of alternation within the limits which obtain in electric lighting (that is, from about 50 to 120 alternations per second) being practically *nil.*

A simple form of gravity ammeter is that shown in fig. 69, and made by the Société des Téléphones de Zurich. The indicating needle is attached to a peculiarly shaped tongue of very thin soft sheet iron, A, which is furnished at intervals with a number of holes. These holes afford a means of adjusting the sensibility of the instrument and making the scale open near any desired reading.. As the current passing through the coil increases in strength the tongue is drawn up into the bobbin and the needle made to pass over the scale on the face of the instrument.

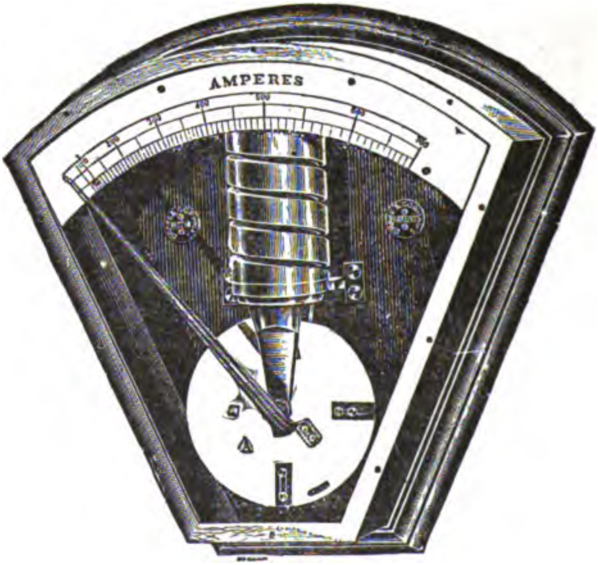
The 'Steel-yard' ammeter, made by the Electrical Power Storage Company and illustrated in fig. 70, is a useful and interesting piece of apparatus. It consists of a coil of thick wire, which, for heavy currents, is simply a copper rod bent into a spiral and enclosing a soft iron core, which, on being magnetised, attracts a soft iron armature attached to one end of the steel-yard lever. A sliding weight is suspended from the other arm of the lever, its position being adjusted until it just balances the force of attraction between the core and its armature. This instrument is very convenient from the fact that its sensitiveness can be varied in several ways, such as varying the weights, &c. The range can also be varied by varying the length of the lever. The range of each instrument is considerable, the one illustrated being designed to indicate from 50 to 250 amperes.

FIG. 70.



The 'Disc' ammeter of Messrs. Drake and Gorham (fig. 71) is another useful and simple instrument. It consists of a spiral of copper ribbon enclosing a soft iron core, having for its armature a soft iron disc A. When the pointer stands at zero, as shown in the figure, the centre of gravity of the disc is just below the suspending pivots, which are carried by two pieces of brass attached to the core, the disc rotating between them. A small segment of the disc is cut off so as to form a slight prominence, which serves as a means of, to some extent, concentrating the magnetic lines of force at a definite point. As the strength of the current increases the attraction of this portion of the disc causes the heavier section to be raised against the force of gravity. A light non-magnetic index needle is fixed to the disc, and as the latter rotates the needle travels over a clear open scale.

FIG. 71.



The lineman's detector (figs. 72 and 73) is a very handy instrument when used for tracing circuits and localising faults, but it must not be regarded as a measuring instrument. It consists of two ordinary instrument bobbins, mounted vertically, and each wound with two coils of wire, one consisting of a few turns of thick

FIG. 72.

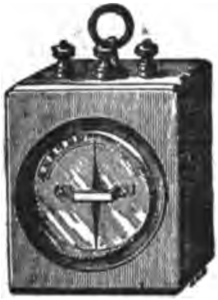
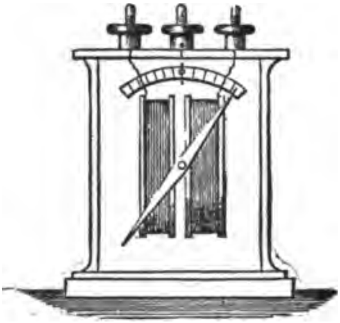


FIG. 73.



wire and the other of many turns of fine wire. The former is usually wound to 0·2 ohm, and the latter to about 100 ohms. A

FIG. 74.

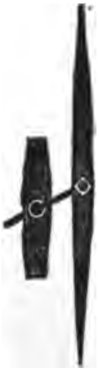
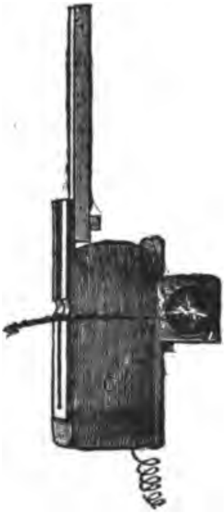


FIG. 75.



shunt coil is sometimes added to the thick wire coil to reduce its sensitiveness. The magnet is about an inch long, and is mounted on a horizontal axis (see fig. 74), so that it can turn freely inside the coils, a long non-magnetic indicating needle being also fixed on the front end of the spindle and moving over a graduated dial. Sometimes a soft iron needle is substituted for the magnetised steel one, it being magnetised by the induction of two powerful steel magnets fixed to the bobbins, one of which is shown at *m* in fig. 75. These magnets can be curved so as to fit into a case of ordinary dimensions.

One end of each of the coils is connected to one or other of the outer terminals on the top of the case, the other two ends being both joined to the centre terminal. Constructed as described, the needle should be deflected through 40° or 50° by a current flowing through the thin wire coil of 9·3 milliamperes—that is to say, by a single Daniell cell having an internal resistance of 7 ohms. The thick wire coil should, with the same cell giving a current of 139 milliamperes, cause a deflection of 20° to 30°

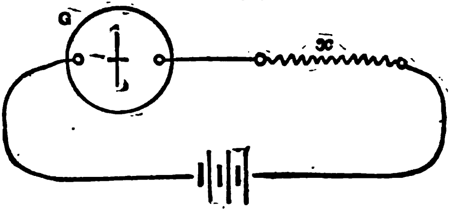
CHAPTER V.

MEASUREMENT OF RESISTANCE.

WHEN the difference of potential in volts between the two ends of a wire is known, and also the current in amperes which that difference of potential is able to maintain in the wire, then the resistance of that wire in ohms may easily be calculated, for by Ohm's law it is equal to the number of volts divided by the number of amperes, or $R = \frac{E}{C}$, where E stands for the electro-motive force in volts, C for the current strength in amperes, and R for the resistance in ohms. If, for instance, a difference of potential or an electro-motive force of 15 volts between the two ends of a wire were able to maintain a current of 2 amperes through it, then its resistance would be $\frac{15}{2} = 7{\cdot}5$ ohms. But if the resulting current were only 2 milliamperes, then the resistance would be $\frac{15}{{\cdot}002} = 7500$ ohms. With one of the instruments described in the preceding chapter, the current flowing may be measured, and in the next chapter we shall show how the difference of potential between any two points of a circuit may be measured in volts; and this method is perhaps the very best that can be devised for finding the value of very low resistances. But sometimes we know the maximum difference of potential or electro-motive force which a certain current-generator can produce, and this knowledge will enable us in certain cases to calculate resistance after merely measuring current strength.

If we have a battery of which we know the electro-motive force, say 10 volts, and also the internal resistance, say 20, we may use it to send a current through the tangent galvanometer, G, and the unknown resistance, x, by joining them all in series as shown in fig. 76. Suppose the resulting current to be 20 milliamperes as measured by the tangent galvanometer, then we may find the *total* resistance of the whole circuit by dividing the electro-motive force by the current. The total resistance will be $\frac{10}{\cdot 02} = 500^{\omega}$. Now, the resistance of the battery and galvanometer is 340^{ω}; if we subtract this from the total resistance we get the value of the unknown resistance, x, that is, $500 - 340 = 160$ ohms.

FIG. 76.



By using the thick wire coils of the galvanometer, and a battery of very low resistance as compared with that of the unknown resistance, no serious error will be made by ignoring the resistance of the battery and galvanometer, and regarding the unknown resistance as the total resistance of the circuit. Under these conditions a number of fairly high resistances may be easily compared, for the same electro-motive force will send through each a current which is inversely proportional to the resistance. Thus, if with three resistances, a, b, c, we get deflections of 30, 25, and 60 tangent divisions respectively, then, $a : b : c :: \frac{1}{30} : \frac{1}{25} : \frac{1}{60}$,

that is, $a : b : c :: 10 : 12 : 5$.

Presuming the galvanometer to be so adjusted that a deflection of 30 tangent divisions is obtained when a current of 10 milli amperes is passed through the thick wire coil, and the battery employed to have an electro-motive force of 2 volts, then the resistance of $a = \frac{2}{0 \cdot 01} = 200^{\omega}$. Therefore, the resistance of $b =$

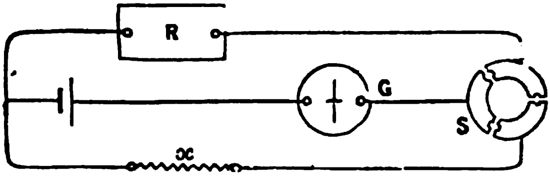
240°, and of c = 100°. As previously stated, however, the resistance of the battery and of the galvanometer must be taken into account, unless they are very low indeed as compared with the unknown resistances.

It should here be observed that in most of the tests to be described it is necessary that a set of resistances whose values are known exactly should be provided. The accuracy of the results obtained depends, in a very great measure, upon the accuracy of the values given to these resistances, so that great care should be exercised in their manufacture, measurement, and use. In Chapter II. some of the principal causes of inaccuracy were enlarged upon, and it was shown how, by avoiding them, a reliable set of resistance coils might be produced.

Assuming such a set of coils to be available, let us now discuss its utility in helping us to ascertain the resistance offered by other conductors.

If a wire, whose resistance we desire to ascertain, is joined up with a battery and galvanometer, the current flowing will deflect the galvanometer needle through a certain angle; let this angle be accurately noted. Then, if the unknown resistance is removed from the circuit, and a box of coils of known resistance inserted in its place, this same deflection may be reproduced by varying the amount of resistance introduced by means of the plugs or arms, as described in Chapter II. The current then deflecting the needle will manifestly be exactly the same in strength as in the first case, and therefore (since the electro-motive force of the battery is unaltered) the total resistance of the circuit must be the same as before. Hence the resistance in the box is equal to the unknown resistance. A convenient way of taking this test is shown in fig. 77. R is the set of resistance coils, x the unknown resist-

FIG. 77.



ance, and S is a three-way plug switch, consisting of three pieces of brass, any two of which may be joined together by inserting a brass plug in the holes provided for the purpose between them. By means of this switch, either x or R may be rapidly placed in circuit, and it is advisable to take a second test after R has been adjusted, to make sure that the electro-motive force of the battery has not been altered by polarisation and so have varied the value of the test. The galvanometer, G, should be a sensitive one; it should, in fact, under all conditions indicate the alteration in the current strength, caused by the addition or subtraction of the coil of lowest value in the resistance-box. As by this method the same deflection is reproduced, any form of galvanometer will answer the requirements, providing only that it is sufficiently sensitive.

Supposing, however, a tangent galvanometer and a battery, both of very low resistance, to be available, the currents which the battery can send through a known and an unknown resistance can be compared directly by the deflections of the galvanometer needle, for if there are, say, 50 tangent divisions in the first case and 45 in the second, and the known resistance is 32 ohms, then

$$45 : 50 :: 32 : x,$$

because the deflection in each case will be inversely proportional to the resistance in circuit. Hence, $x = 35{\cdot}5$ ohms. The three-way plug switch may be used as in the last test, but both readings should be taken near the 'angle of maximum sensitiveness,' viz. 45°.

When, however, the resistances of the battery and galvanometer are comparatively high, their values must be known or ascertained, and allowed for in accordance with Ohm's law as follows: Let the resistance of the galvanometer, G, be 320^{ω}, that of the battery $r = 12^{\omega}$, and the known resistance $R = 560^{\omega}$; let the current with R in circuit (C_1) give 50 tangent divisions, and with x in circuit (C_2) give 45 tangent divisions.

Then, in the first case,

$$C_1 = \frac{E}{R + G + r} \text{ whence } C_1(R + G + r) = E,$$

and in the second case,

$$C_2 = \frac{E}{x + G + r}, \text{ whence, also, } C_2(x + G + r) = E,$$

therefore $$C_2(x + G + r) = C_1(R + G + r),$$

whence $$x = \frac{C_1}{C_2}(R + G + r) - G - r.$$

Since $\frac{C_1}{C_2}$ is merely a ratio, the strength of the currents in milliamperes need not be known, the number of tangent divisions produced by the currents being inserted instead of C_1 and C_2. Inserting all the values, then, we get

$$x = \frac{50}{45}(560 + 320 + 12) - 320 - 12$$
$$x = 659{\cdot}1 \text{ ohms.}$$

The resistance of the galvanometer is nearly always known and engraved on the instrument, but it is frequently necessary to measure the resistance of the battery at the time of making the test. To avoid this it is better to use a battery of very low resistance, and this may usually be obtained by joining up several sets in parallel.

The equation will then stand :

$$x = \frac{C_1}{C_2}(R + G) - G.$$

By inserting the values as before we can see the amount of the error caused in this case by ignoring the battery resistance of 12 ohms.

$$x = \frac{50}{45}(560 + 320) - 320$$
$$x = 657{\cdot}\dot{7} \text{ ohms.}$$

The error is thus but 1·3"; and it is not difficult to get a battery of only about 1 ohm resistance to send a sufficiently strong current for the above test, when the error would be negligibly small.

This method also provides us with a means of measuring the resistance of a galvanometer. For, let the second reading be taken through a known resistance $K = 700^{\omega}$ instead of x, then, ignoring the battery resistance, it follows that, as before,

$$C_1(R + G) = C_2(K + G)$$
$$C_1R + C_1G = C_2K + C_2G$$
$$G(C_1 - C_2) = C_2K - C_1R$$
$$G = \frac{C_2K - C_1R}{C_1 - C_2}.$$

Inserting the values we get

$$G = \frac{45 \times 700 - 50 \times 560}{50 - 45} = 700 \text{ ohms.}$$

With the same apparatus the internal resistance of the battery may be measured. For if the battery is joined up to the low resistance coil of the galvanometer (three or twelve turns), practically the only resistance in the circuit will be that of the battery x. If possible, the adjustable magnet should be placed so that the deflection is, say, 50 tangent divisions. Now, it will be evident that to *halve* the current flowing, the resistance in the circuit must be *doubled*. If, therefore, resistance R is inserted until the deflection falls from 50 to 25 divisions, the resistance R will be equal to the resistance x of the battery.

Sometimes, however, the effect of the controlling magnet is insufficient to produce a convenient deflection, and it is then necessary to introduce some resistance in the first test, say P, for this purpose. Then

$$C = \frac{E}{x + P}, \text{ or } C(x + P) = E.$$

If, now, P is increased to R in order to halve the deflection, and therefore halve the current strength,

then $$\frac{C}{2} = \frac{E}{x + R}, \text{ or } \frac{C}{2}(x + R) = E,$$

therefore $$\frac{C}{2}(x + R) = C(x + P),$$

whence $$x = R - 2P.$$

For instance, if with a low-resistance galvanometer it is found necessary to insert 11 ohms in order to bring the deflection down to 60 divisions, and to increase this resistance to 31 ohms in order to make the deflection 30 divisions, then the resistance of the battery $x = 31 - 22 = 9$ ohms.

In some cases the resistance of a cell is so very low that it becomes a difficult matter to measure it with great accuracy. Secondary cells, especially, have not only a low resistance, but also a comparatively high E.M.F., so that some special method is necessary in dealing with them, if great accuracy is desired.

A very pretty method consists in allowing the cell to send a current through a low external resistance of known value, and then measuring the fall of potential which takes place along this resistance. This fall can be easily found by subtracting the external potential difference from the total E.M.F. developed. As the resistance of each portion of the circuit is proportional to the fall of potential taking place along it, the internal resistance of the cell can then be deduced. One of the hot-wire voltmeters (page 189), designed to indicate up to 2·5 volts, is a useful piece of apparatus for this work. The total E.M.F. of the cell can be measured by joining the voltmeter to the cell terminals, because the high resistance of the voltmeter allows only a feeble current to be generated, so feeble, in fact, that the fall of potential inside the cell is exceedingly low; whence the potential difference indicated is practically equal to the E.M.F. developed. If a second external conductor, but of low resistance, is also joined to the terminals of the cell, the total external resistance will be considerably reduced, and the fall of potential inside the battery proportionally increased, and a lower E.M.F. will be indicated by the voltmeter. Consequently, if we denote the total E.M.F. by E, the fall of potential in the external and internal portions of the circuit by P and p respectively, the resistance of the cell by r, and of the known external resistance by R, it is evident

$$E - P = p,$$

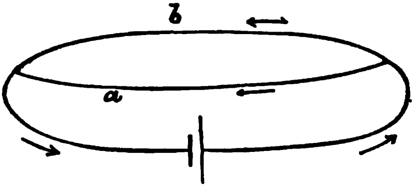
and $$P : p :: R : r;$$

from which we get $$r = \frac{p R}{P}.$$

When a battery of such cells is to be measured—say twenty—it is better to reverse nearly half of them—in this case, nine; then the resistance to be measured is that of twenty cells, while the E.M.F. urging a current through them is only that of two cells.

The method next to be described depends upon the fact that if two conductors of exactly equal resistance are joined up 'in parallel' and placed in a circuit, as shown in fig. 78, the current will divide equally between the two—that is, the current in *a* will be exactly equal to the current in *b*. The converse of this holds good, viz. if we have two conductors so joined up in parallel, and we know that the current in *a* is exactly equal to the current in *b*, then we are certain that the resistance of *a* is exactly equal to the resistance of *b*.

FIG. 78.

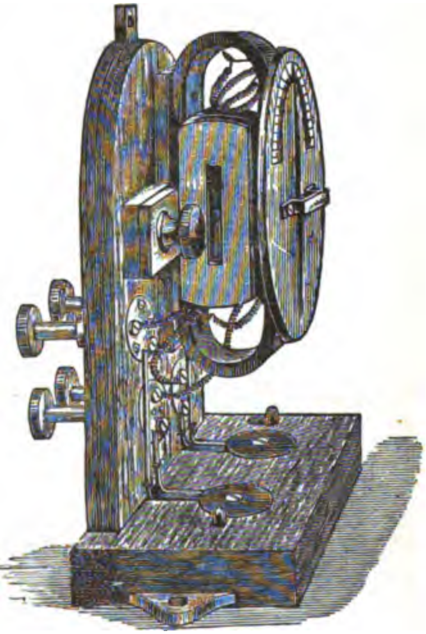


The 'Differential Galvanometer' is an instrument for showing when the currents in two branch circuits are equal. In principle it is very simple. It consists of a magnetic needle, either pivoted horizontally or vertically, surrounded by *two* distinct coils of wire of exactly equal resistance, and wound so as to act with equal force on the needle. If, therefore, a current is sent through one coil, and a current of equal strength through the other *in the opposite direction*, their effects will be neutralised one by the other, and the needle will not be deflected. Figs. 79 and 80 illustrate a really good form of differential galvanometer, for ordinary work, which is used in the telegraph service.

The soft iron needle is vertical, but the arrangement for keeping it strongly magnetised is somewhat peculiar.

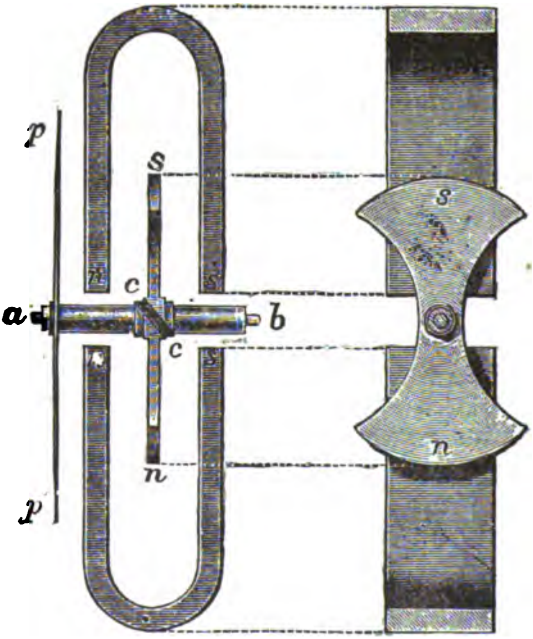
Fig. 80 shows side and front elevations of the needle and magnets. The spindle, which is pivoted at *a* and *b*, is rather massive, and a piece of brass is inserted obliquely at *c c*, as shown, thus breaking its magnetic continuity. Each half of the needle. *n s*, is fixed at right angles to one half of the spindle at this point, and the whole is embraced by two horse-shoe magnets, placed with their like poles adjacent, as shown in the figure. These magnets form a very strong field in the space in which the spindle lies. A large number of the lines of force pass through the spindle, but when they reach the break in the iron at *c c* they bend upwards through the soft iron needle from one side, and downwards from the other side, the result being that the needle is a powerful magnet with its north pole downwards. On the end of the spindle is fixed a blackened brass pointer, *p p*, which, passing over or in front of a circular dial divided into degrees, indicates the movements of the needle. The two wires, each offering 50° resistance, are wound side by side over two separate bobbins, so that the corresponding portions of each wire are equally disposed in relation to the needle and exert equal magnetic effects upon it. This method is, of course, far in advance of the old instrument-makers' method of winding one wire alone on one bobbin and the other on another bobbin. The tests for a differential galvanometer are that, if powerful but equal currents are sent in opposite directions through the coils, no effect should be produced upon the needle: each coil used separately should produce equal but opposite deflections with the same current, and the coils should offer exactly the same resistance. The inner ends of the two wires on the bobbins are respectively joined together and the other four ends connected to as many terminals

FIG. 79.



on the back of the instrument. This allows the current to be sent through the coils in several ways. First through one coil only, resistance 50^{ω}. Secondly, through both coils in series in such a direction that they act upon the needle in the same manner, when the resistance will be 100^{ω} and the deflective action doubled, provided the increase of resistance does not sensibly reduce the current. Thirdly, through both coils in parallel and in the same direction; the resistance in this case will be 25^{ω}, and the deflective action the same as that of *one* coil only. Fourthly, through both in parallel, but in opposite directions, when the needle should, as already stated, be unaffected. Lastly, through both coils in series in opposite directions, when the needle should also be unaffected. This last method of joining up is also useful for proving if the deflective effects of the two coils are

Fig. 80.



equal, for the same current passes through each irrespective of their resistance.

Although the wires are wound side by side throughout, it is very rarely that they are found to act with equal force on the needle. There are three ways of attaining this result without affecting the resistance. The position on the bobbins of a portion of either or both of the wires may be altered; or a part of the wire which has the greater effect may be unwound and wound back on the bobbin in the opposite direction; or the stronger may be unwound until an exact balance is obtained, when the length so unwound may be coiled up in the base of the instrument, where, if wound 'double,' it will have no effect on the needle.

The lower end of the needle is weighted, to keep it in the vertical position and to restore it to that position on the cessation of the current; and the current acts against this weight when it deflects the needle. The *arm* at which this weight acts increases with the deflection of the needle, so that the angle of deflection cannot be proportional to the current strength. The relation between the two is, in fact, irregular, because of the peculiar shape of the needle (shown in fig. 80), and because the field due to the current, although almost uniform inside the coil, is far from being so near the edges and just outside.

But at present we shall only consider the use of the instrument with the needle at or near zero, at which point, it may be mentioned, it is most sensitive.

Provided with this instrument, a battery, and a set of resistance coils of sufficient range, we are in a position to rapidly measure unknown resistances.

Fig. 81 shows the best way of making the connections. G is the galvanometer, R a set of resistance coils, x the unknown resistance, and K a key for closing the battery circuit. On depressing the key, the current will divide at $a\ c$, the junction of the two coils of the galvanometer, part passing through the coil $a\ b$ and R, and the remainder through the other coil $c\ d$ and x, back to the battery.

Supposing R to be of less resistance than x, then a greater part of the current will pass through $a\ b$ and R than through $c\ d$ and x, consequently the needle will be deflected to one side. By increasing R this excess of current will be diminished, and the deflection of the needle also decreased, until the needle again stands at zero. Then the currents flowing through both coils of the galvanometer are equal, and therefore the resistance of both branches must be equal, viz.

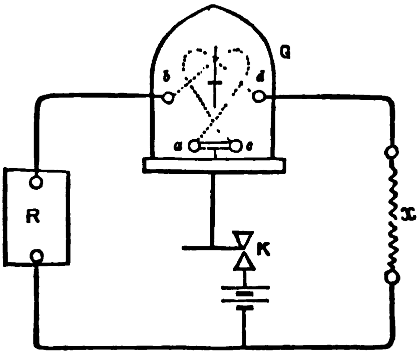
$$x + 50^{\omega} = R + 50^{\omega}.$$

that is,

$$x = R.$$

By further increasing R the needle would be again deflected. but in the opposite direction to that previously obtained.

FIG. 81.



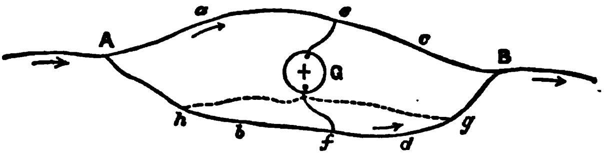
Before making a test it is advisable to find out and note in which direction the needle is deflected when R is too large or too small, so that immediately the needle moves to one side or the other we may know whether it is required to increase or decrease R.

It may be necessary to measure resistances which are either higher or lower than any which can be inserted in the box R. The range can then be extended by shunting one coil of the galvanometer — say by a wire one-ninth of the resistance of the coil. Then, as only one-tenth of the current in that branch will pass through the galvanometer coil, a balance will be obtained when the total resistance in that branch is one-tenth of the resistance of the other. For instance, suppose the coil of the galvanometer connected to R to be so shunted, and a balance to be obtained, when the resistance in R amounted to 650 ; then the unknown resistance would be 6,500$^{\omega}$ nearly. We say nearly, because, in order to obtain a perfectly accurate result, compensating resistance must be inserted to make the resistance of the shunted galvanometer coil equal to 50$^{\omega}$, as explained in the preceding chapter.

In measuring electro-magnets or any single wound coils, a sudden jerk of the needle, due to self-induction (see Chapter VII.), will always be noticed on making and breaking the circuit. In such cases care should be taken to see that the needle rests at zero when no current is flowing, and then the key should be depressed and the adjustments made with a steady uninterrupted current until the needle again comes to zero.

The differential galvanometer, although a first-rate instrument for comparing two resistances by the equalisation method, loses in simplicity and rapidity when shunts have to be used and allowed for. By means, however, of a piece of apparatus known as the 'Wheatstone Bridge,' the value of any resistance can be readily measured. The principle of this invaluable apparatus is very simple, and is explained by the diagram (fig. 82). Let us suppose two wires, A *a c* B and A *b d* B, either equal or unequal in resistance, to be joined up in parallel and a current sent through or divided between them, as shown in the figure. The current will, as already explained, divide itself between the two wires inversely as their resistances, but, for our present purpose, the current strength is a matter of little or no importance.

FIG. 82.



If, now, one end of a galvanometer coil, G, is joined to any point, *e*, in one wire, and the other end to a point, *g*, in the other, very near to the junction B, a deflection of the galvanometer needle will be observed, indicating a current flowing from *e* to *g*.

On removing the galvanometer wire from *g* and joining it to another point, *h*, also in the second wire, but very near to A, the galvanometer will again indicate a current, but flowing in the reverse direction, viz. from *h* to *e*. If contact were successively made at points along the wire A *b d* B farther from A, the current would become feebler and feebler until, finally, a point, *f*, would be found at which the needle would not be affected at all, showing the absence of a current through the galvanometer.

There can be but one explanation to these experiments. It was clearly laid down and demonstrated in Chapter II. that whenever a current of electricity flows, it does so invariably in virtue of a difference of potential between the extremities of the conductor through which it flows, and, conversely, whenever the extremities of a conductor are at different potentials a current flows through it. These two facts must never be lost sight of, for they constitute the key to a host of electrical phenomena and problems. Inasmuch, then, as it was seen, by the evidence of the galvanometer, G, fig. 82, that a current passed through it when its terminals were connected to the points *e* and *g*, and to the points *e* and *h*, the current or currents flowed as a consequence of a difference of potential between those points. And the absence of a current on connecting the points *e* and *f* together is an equally clear proof that those two points were at the same or equal potentials. If we suppose A to be at a higher potential than B, and connect the galvanometer directly to those points, so that it shall share the current arriving at A, the needle will be deflected to one side or the other, the particular deflection being governed by the direction of the current round the needle. Let us suppose the deflection to be to the right. Then, on connecting the galvanometer to A and *g*, or even to *e* and *g*, the deflection will also be to the right, and will establish the fact that the potential at *e* is higher than that at *g*. On the other hand, the opposite deflection which is obtained when the galvanometer is connected to *e* and *h* affords ample proof that the potential at *h* is higher than that at *e*. Now, as the ends of the two wires at A are always at the same potential, and as the ends at B are also at the same potential, although lower than that at A, it follows that the fall of potential along A *a c* B must equal that along A *b d* B. It also follows that if we fix upon any one point in either of the wires, there must always be a point somewhere in the other wire which will be at exactly the same potential, and if these two points are connected together no current can possibly flow between them. Herein is the underlying principle of the Wheatstone bridge.

We must now endeavour to discover what relation, if any, exists between the resistances of the four sections into which these wires are divided. Let the resistance of the section between A and

e be denoted by a, that between A and f by b, between e and B by c, and between f and B by d.

The difference of potential between A and e is equal to that between A and f; call this P_1.

Again, the difference of potential between e and B is equal to that between f and B; call this P_2.

Now we have seen that in every case (since by Ohm's law $E = CR$) the difference of potential between any two points is equal to the current flowing, multiplied by the resistance of the conductor between those points.

Suppose the current flowing in the upper branch, A e B, to be C_1, and that in the lower branch, A f B, to be C_2.

Then $$P_1 = C_1 \times a;$$

also $$P_1 = C_2 \times b;$$

therefore $$C_1 \times a = C_2 \times b,$$

or $$\frac{a}{b} = \frac{C_2}{C_1}.$$

Again, $$P_2 = C_1 \times c,$$

also, $$P_2 = C_2 \times d,$$

therefore $$C_1 \times c = C_2 \times d,$$

or $$\frac{c}{d} = \frac{C_2}{C_1}.$$

But $\frac{a}{b}$ is likewise equal to $\frac{C_2}{C_1}$;

consequently $$\frac{a}{b} = \frac{c}{d}$$

This is the relation between the resistances which we sought to discover, and we might, in the same way, prove that it holds good for other cases where the resistances have different values.

The relation may also be viewed from another standpoint. The fall of potential along a conductor is proportional to its resistance, and, conversely, the resistance of a conductor is proportional to the fall of potential which takes place along it. Now, the total fall of potential along the two branches (fig. 82) is equal in amount, and the potential at e is equal to that at f; and the fall along a is equal to the fall along b, and also the fall taking place along c is equal to that along d. Therefore, the value of the resistance a bears to that of c the same ratio as does b to d; that is

$$a : c :: b : d,$$

or

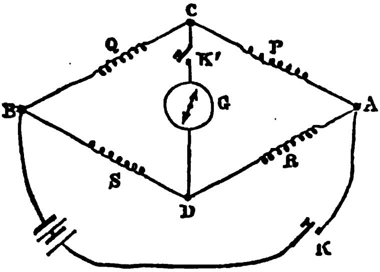
$$a : b :: c : d.$$

If one of these resistances, say c, were unknown, and the other three known, we could readily determine the value of c, for $c = \frac{ad}{b}$.

This is, in fact, the method by which resistance is measured with the Wheatstone bridge.

We have four resistances, P Q R S, one of which, say P, is unknown and the others known, and join them up as in fig. 83.

FIG. 83.



The junctions at A and B are maintained at different potentials by means of a suitable battery, while to the other junctions, C and D, a galvanometer is connected. The known resistances are then varied and adjusted, until the absence of a current through the galvanometer proves C, the junction of P and Q, to be at the same potential as D the junction of R and S.

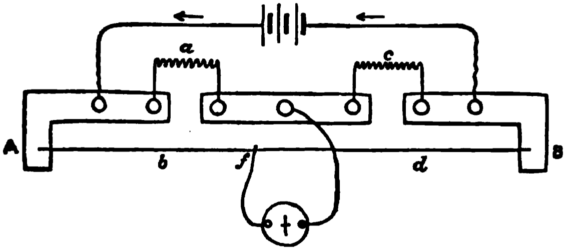
The value of P can then be calculated, as above, the simplest case being when Q = S, for then P = R. Two keys, K and K^1, are provided for the purpose of disconnecting the battery and galvanometer circuits respectively.

There are various ways of performing the necessary adjustment of the known resistances.

In the case shown in fig. 82 we found the point of equilibrium by shifting one of the wires connected to the galvanometer along A b d B, thus varying the *ratio* of the resistances b and d; and a very good form of bridge for measuring low resistances may be constructed upon this principle.

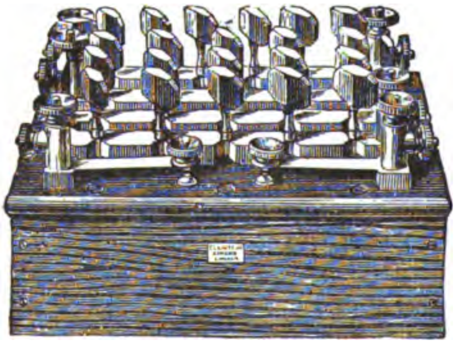
Three brass or copper strips, so stout as to have practically no resistance, are fixed on to a mahogany board, as in fig. 84. Between the ends of two of these strips a wire, A B, is stretched. It is convenient to have this wire one metre in length, with a scale placed under it, divided into a thousand parts. There are three terminal screws on the middle strip, and two on each of the others. The unknown resistance, c, is connected to the two adjacent ends of the middle and right-hand strips, while a known resistance, a, is joined to the adjacent ends of the other two. A battery is joined up to the outside strips, and a current can thus be sent through the branch a and c, and the branch b and d, in parallel. One end of the galvanometer coil is joined to the terminal screw at the junction of a and c, where the potential will have fallen to a certain amount. The other is connected to a slider which passes along over the wire b d, and which, when pressed down, makes contact with the wire, and allows the exact point at which contact is made to be read on the metre scale. As previously explained, a point, f, is sought for, at which, contact being made, no current flows through the galvanometer. Then $c = \frac{d}{b} \times a$. It is clear from this equation that $\frac{d}{b}$ is merely a ratio, and need not be known in ohms. If the wire A B is of uniform resistance throughout, it is sufficient to know the length in millimetres of b, and the length in millimetres of d; but the resistance of a must be known in ohms. Supposing a were $2{\cdot}5$ ohms, and a balance to be obtained with the slider at a point 440 millimetres from A; then $b = 440$, and $d = 560$. Therefore $c = \frac{560}{440} \times 2{\cdot}5 = 3{\cdot}18$ ohms.

FIG. 84.



The stretched wire must be of considerable resistance so as to make the fall of potential per unit of length appreciable, and it should be of some hard durable metal, otherwise it would become worn by the slider and its uniformity of resistance destroyed. For these reasons the wire should be made of German silver, platinum silver, or platinoid. A key should be inserted in the battery circuit, to prevent the current being kept on longer than necessary, and heating the wires. Extra resistance in the galvanometer or battery circuits introduces no error, merely reducing the sensitiveness of the arrangement. But it is important to secure good clean connections in the other branches, as any resistance introduced there might cause a great error in the result. To obtain the best results the resistance of the battery should be low and its E.M.F. high; the resistances in the arms of the bridge should not differ very greatly, and the galvanometer must, of course, be sufficiently delicate to indicate the difference of potential caused by moving the slider through the shortest measurable distance. But the length of the wire on the galvanometer must not be indefinitely increased to attain this result, otherwise the resistance so added reduces the current in a greater proportion than the deflective effect is increased.

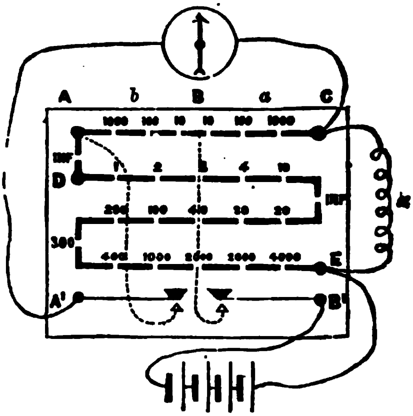
FIG. 85.



There is, in fact, for every separate test, a certain resistance which it would be best to give the galvanometer. In practice, however, we can do no more than wind the galvanometer in such a manner as will make it best suited to the average conditions under which it will be employed. For an ordinary slide-wire bridge the galvanometer resistance should not greatly exceed one ohm.

The slide-wire bridge answers well in a laboratory, and is exceedingly valuable for measuring low resistances. A more practical form of the Wheatstone bridge and one which is very largely used for general work is shown in fig. 85, and its connections in fig. 86.

FIG. 86.



There is no exposed stretched wire here, but all the resistances are placed in a mahogany box with an ebonite top, their ends being connected to brass blocks fitted with plugs as in the case of any ordinary resistance-box. These resistance coils are measured with extreme care, and the value of each in ohms is marked (often indistinctly, by the way) upon the ebonite. Double terminal screws are employed to avoid risk of resistance being introduced by the careless connection of two wires on to one terminal. In the general view it will be seen that there are two keys, each, when depressed, making contact with a metal stud; these keys are marked A′ B′ in fig. 86. A terminal screw is connected to each key, and to the right-hand one is joined the zinc pole of the testing battery. The stud under this key is connected beneath the ebonite cover to the brass block B in the middle of the back row of resistances, so that the zinc pole of the battery is joined to this block when the right-hand key is depressed. It is at this point then, corresponding to B, the junction of Q and S in fig. 83, that the current divides, and on either side are three coils of 10, 100, and 1,000 ohms respectively, any or all of which can be inserted at pleasure. At each end of this row of coils is a terminal screw, and the galvanometer is joined up to these points. But, as we have seen, it is necessary to have a key in the galvanometer circuit, and i is very convenient to place both keys close together, as shown. One wire from the galvanometer is therefore brought to terminal

A′—that is, to the left-hand key—and the stud under this key is connected to terminal A, as shown by the dotted line. Therefore, when A′ is depressed, this side of the galvanometer is joined to terminal A. The other side of the galvanometer goes direct to terminal C. The two 'arms' of the bridge, B A and B C, correspond to S and Q in fig. 83, and the arm marked R in that figure here consists of a number of coils, ranging from 1 ohm to 4,000 ohms, placed between the terminals D and E. We have thus three arms of the bridge of known values, and the fourth, or unknown resistance, x, is placed between terminals C and E. The copper pole of the battery is brought direct to terminal E, which corresponds to the junction of P and R in fig. 83. Between the arms B A and D E—that is, between the terminals B and D—is a space marked 'infinity.' There is no coil connected to the two blocks at this point, so that the resistance is infinite, that is, the circuit is disconnected when the plug is removed. This arrangement is exceedingly useful, for it is possible to increase the range of measurement considerably, by removing the plug and inserting an extra box of coils in the circuit here; and further, it is often convenient, in some tests, to be able to separate the coils into two independent sets. There is a second 'infinity plug' between the 10 and 20 ohm coils, and when using the apparatus simply as a set of resistance coils these plugs may be used as keys for disconnecting or joining up the circuit.

Now, suppose the bridge to be properly joined up, with an unknown resistance x, the value of which it is desired to find, between C and E.

It is clear that A and C are the points which we want, by adjusting the various resistances, to bring to the same potential, and the galvanometer is connected to these points so as to indicate when this result is attained. We begin by inserting some resistance in the arms B A and B C, say 100 ohms in each. These resistances are not again altered during the measurement, but the adjustment is made by varying the amount of resistance in the arm D E until the galvanometer shows that a balance has been obtained. When this happens the value of the unknown resistance, x, is equal to the amount which has been inserted in the arm D E. Much time may be saved and greater accuracy ensured by taking a test methodically, and the following points should be attended to. Before starting it should be ascertained that the plugs are firmly in their places and that all the connections at the terminals are good, and to ensure this it is advisable to take advantage of the double terminals provided, and place only one wire on each screw. The galvanometer having been placed in a position convenient for the experimenter, some coils in each of the three arms must be put into circuit, the amount in the arms D E being made as near the unknown resistance as can be guessed. The right-hand key should be depressed and then, a moment afterwards, the left-hand key, and the galvanometer observed; probably the latter will indicate the passage of a current, and it should always be found which way the needle moves when the resistance in the arm D E is, say, too high. If that is done, one can see, immediately the needle moves, whether it is necessary to increase or reduce the resistance in D E in order to get a balance. This is much quicker than obtaining the balance at random. The galvanometer key must only be lightly tapped so as to just indicate in which direction the resistance must be varied, until a balance is nearly obtained, when it may be held down for a longer period. This prevents a heavy current being passed through the galvanometer; and the student will hardly require warning that if the battery is kept on too long the coils will become more or less heated and their resistance varied. It should also be borne in mind that with a very delicately made instrument a suddenly applied heavy current is likely to injure the needle or the pivot.

We considered above the simple case when the resistances of the arms B A, B C were equal, but the bridge is not always used under these conditions.

If, for instance, the unknown resistance is comparatively low and we desire to measure it to within a fraction of an ohm, it is then necessary to have these arms of unequal resistance; we should, in fact, make B A 100 ohms and B C 10 ohms. Then, if a balance were obtained with 13 ohms in D E, x would be equal to 1·3 ohms. For, by the principle of the bridge,

$$x = \frac{\text{BC} \times \text{DE}}{\text{BA}} = \frac{10 \times 13}{100} = 1{\cdot}3.$$

And by using 1,000 ohms in B A and 10 in B C, measurements to within $\frac{1}{100}$ of an ohm might be made.

When the unknown resistance is very high, then the ratio must be reversed, taking, say, 10 in B A, and 1,000 in B C. If, now, a balance is obtained with 1,309 ohms in D F, then

$$x = \frac{1000}{10} \times 1309 = 130900 \text{ ohms.}$$

When using this ratio it is not always possible to obtain a perfect balance and so determine the unknown resistance exactly, because the lowest unit in the arm D E is 1 ohm, and this is equivalent to 100 ohms in the unknown resistance. For instance, if in the last test the unknown resistance were 130,925 ohms, it would be necessary to increase the resistance in D E by a quarter of an ohm in order to get a perfect balance, and this fraction is not at our disposal. A supplementary set of resistances having fractional values may be inserted between the terminals A and D, provided that the arrangement is sufficiently sensitive for the galvanometer to respond to the change produced by these fractions of an ohm; but for general work it is sufficient to know the value of a very high resistance to within 10 or 20 ohms, and this can always be estimated by observing the movements of the needle when the resistance in D E is less than 1 ohm too high and less than 1 ohm too low.

It may be remarked that the efficiency of the Wheatstone bridge is reduced by the injudicious choice of a battery, more frequently than by any other cause.

The point to be borne in mind is, that a considerable fall of potential is necessary along the arms of the bridge, that is, between the points A and B in fig. 82. The greater the difference of potential between these points, the greater will be the effect on the galvanometer needle for a given change in any of the resistances, and therefore the higher the degree of accuracy to which we can measure. Now, suppose the bridge to be of the slide-wire form, and the resistance of the arms between A and B to be 2 ohms. If we employ a battery of 10 Daniell cells, having a resistance of 5 ohms per cell, the potential difference between A and B will be considerably less than three-quarters of a volt, all the rest of the fall taking place inside the battery. A single Grove cell, having a resistance of ·2°, could maintain about 1·8 volts under similar conditions, although its E.M.F. is only one fifth of that of the Daniell battery. This clearly shows the evil effect of resistance in the battery, and it is evident that when the resistances in the bridge are low, the battery employed, while having a sufficiently high E.M.F., *must* have a very low internal resistance. When, however, the resistances are high, resistance in the battery circuit is not so harmful (as the fall of potential in any part of a circuit is directly proportional to the resistance of that part), and a battery of Daniell cells may be employed. The E.M.F. of the battery is often kept unnecessarily low to avoid a strong current heating the coils; there is, of course, a limit, but by a skilful manipulation of the keys provided, the time during which the current need be kept on is so very short that the heating is inappreciable. We have remarked that it is better to depress the battery key first, and allow the current to become steady before tapping the left-hand key and throwing the galvanometer in circuit. A very short time is sufficient for this, but extra care should be taken that it is done when the unknown resistance is an electro-magnet, or any coil which is liable to the phenomenon of 'self-induction' (see Chapter VII.), or when it has any 'electrostatic capacity,'[1] as in the case of a telegraph line or cable, otherwise the needle will move violently, although the actual resistance may be truly balanced. To enable the student to understand how the nature of the resistance can cause the potential at any two points to be widely different when the current is starting or stopping, and yet equal when it is steady, we may employ an analogy. Suppose we have two equal iron water-pipes joined up as in fig. 82, with some piece of apparatus to indicate a difference or equality of pressure, in the place of the galvanometer, the points *e* and *f* being at equal distances from A or B. Then, the pipes being equal in all respects, the pressure at *e* and *f* will always be equal, no matter how the difference of pressure at A and B may be varied. If, now, one branch, A *f* B, is replaced by a very flexible india-rubber pipe of similar dimensions, this no longer holds good. Suppose the pipes to be empty and then water at a high pressure to be forced in at A; the pressure at *e* will rise quicker than at *f* because the flexible pipe expands, and this occupies a short time. When the expansion has reached its limit the pressures at *e* and *f* are equal, but on suddenly stopping the flow at A, the pressure at *f* becomes higher than at *e* for a brief moment owing to the contraction of the pipe.

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[1] The scope of this work will not permit us to deal with this branch of the subject; 'electrostatic induction' has seldom to be contended with by the electric-light engineer.

Somewhat similarly, as we shall see later on, a current of electricity can never rise to its full value, or die away instantaneously; for this reason, the coils of the bridge are so wound that in them the rise or fall is very rapid, and when the unknown resistance is such that the rise or fall takes place at a different rate, the current must be allowed to become steady before the second key is closed.

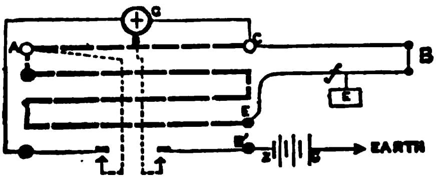
The peculiar method of winding the bridge coils is also useful in preventing any direct action, which might be caused by the current circulating in them, being produced upon the galvanometer needle. When an electro-magnet is being measured, the galvanometer must be placed far enough away to avoid its being affected when the current is passed through the electro-magnet. When there is any reason to suppose that some such effect as this exists, the battery key should be closed and opened several times, the galvanometer key being left open and the needle watched. If it moves at all, we have proof positive that some portion of the apparatus is producing a disturbing effect upon the galvanometer.

We will describe one other test, known as the 'Loop test,' which is rather interesting, and may prove useful to an electric-light engineer.

When both ends of the unknown resistance are not easily accessible, it may be measured by joining one end to the terminal C, and connecting the distant end to earth. The terminal E—that is, the junction of the arm D E—and the copper pole of the battery are also put to earth, and then the test can be made in the usual manner, because the two earth-connected points are at the same potential, and behave in precisely the same way that they would if they were joined to a common terminal. A leakage sometimes occurs in a covered wire or cable, which allows more or less of the current to escape to earth, provided some other point of the system is also earthed. It is necessary to determine the distance of such a 'fault,' or point of leakage, and it might easily be done by disconnecting the line beyond it, and then, treating the fault as an earth, measuring the resistance of the wire up to this earth as described above.

It rarely happens, however, that any fault develops which does not offer considerable resistance to the passage of the current to earth, and as the amount of this resistance is never known it cannot be allowed for. Further, the resistance frequently varies so rapidly that it is not possible to obtain a balance at all, and some different arrangement of the bridge is necessary. We have seen that in the battery circuit extra resistance, and even variable resistance, causes no error in the result, although it reduces the sensitiveness of the bridge: and if this variable earth fault can be placed in the battery circuit, we can ignore its resistance altogether. This can readily be done if both ends of the wire are accessible; if not, it is necessary to have a second or return wire, and connect the distant ends of the two together. This arrangement is shown in fig. 87. The copper pole of the battery is put to earth, the zinc pole being always joined to line in fault-testing, as the current in that direction — usually by an electrolytic effect decreases the resistance of the fault. E B is the faulty wire, the fault being shown at *f*. C B is the sound wire by means of which we reach the other end of the faulty wire, the two being looped together at B. The good wire is joined to terminal C, and the faulty one to E. On depressing the battery key the current flows through the bridge and the lines, finding earth at the fault, and a balance can be obtained in the usual way. Let R be the resistance inserted in A E, and let x represent the unknown resistance of the faulty wire from E to the fault at *f*. Then the total resistance of this arm of the bridge is $R + x$. The other arm consists of the sound wire, C B, and that portion of the faulty

FIG. 87.



wire from B to f. Let the total resistance of this arm be called y. Let a be the resistance in B C, and b that in B A, then

$$a : y :: b : \text{R} + x,$$

that is,

$$y = \frac{a}{b} \times (\text{R} + x) \quad . \quad . \quad . \quad . \quad . \quad . \quad (1).$$

We have here two unknown quantities, x and y, and must therefore get a second simple equation in order to eliminate one of them. It is clear that the total resistance of the two lines is $x+y$, and usually this is known; if not, it can be measured by joining up the bridge in the ordinary way (that is, connecting the copper pole of the battery to terminal E), and measuring the resistance of the loop as if no fault existed; for there will then be no leakage at the fault, as no other part of the system is earthed. Suppose the resistance thus found to be L ohms, then

$$x + y = \text{L};$$

therefore

$$y = \text{L} - x \quad . \quad . \quad . \quad . \quad . \quad . \quad (2).$$

Therefore, from equation (1),

$$\frac{a}{b} \times (\text{R} + x) = \text{L} - x;$$

therefore

$$x = \frac{b\,\text{L} - a\,\text{R}}{a + b}.$$

If we make $a = b$, as is frequently done in this test, then, evidently,

$$\text{R} + x = \text{L} - x,$$

and

$$x = \frac{\text{L} - \text{R}}{2}$$

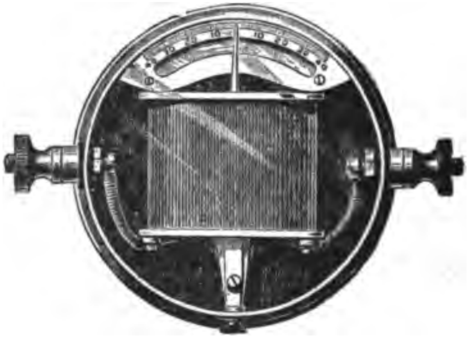
or, we simply subtract the resistance in A E from that of the two lines, and, dividing by 2, obtain the value of x.

Now, x is the resistance in ohms from E to the fault; the length of the wire E B is known, and therefore its resistance per mile, or any other unit of length, is known. Thus we can at once ascertain the distance of the fault in miles or yards by dividing x by the resistance per mile or per yard.

The galvanometer used with the form of bridge above described has a resistance of 800 ohms; it is shown in fig. 88, and is a very good instrument—portable, yet capable of giving evidence of a very small potential difference. When joined up in circuit with a resistance of 20,000 ohms, and a single Daniell cell (the current then being about one twenty-thousandth of an ampere), it will give a deflection of 25°.

The coil consists of many turns of fine silk-covered wire, wound on a single brass bobbin. The needle, which is pivoted, lies exactly in the centre of the coil, and is quite covered by it. At right angles to the needle is fixed a pointer, which projects from the coil, and, passing over a scale and a strip of looking-glass, indicates the slightest movement of the needle. A lever is provided for lifting the needle from its pivot when not in use, and each end of the coil is connected to a terminal which is insulated from the brass casing by ebonite. The features in the design of the instrument which enable it to respond to very feeble currents are the great length of wire employed, the nearness of this wire to the needle, and the excellent pivoting of the needle, which allows it to move easily.

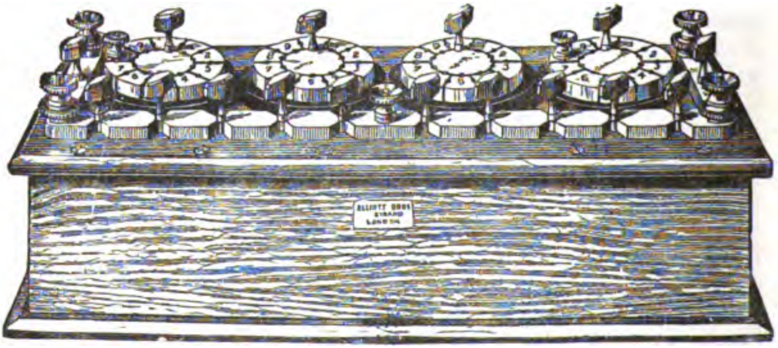
FIG. 88.



Another form of Wheatstone bridge is shown in fig. 89. This has a very great range, and some of its coils are joined up differently to those in the apparatus last described.

The two 'ratio arms' each consist of five coils, of 1, 10, 100, 1,000, and 10,000 ohms resistance, and are connected up in the usual manner. The arm which is varied in balancing is divided into four sets of coils, each set consisting of nine *equal* coils. The resistance of each coil in the first set is 1^{ω}, in the second 10^{ω}, in the third 100^{ω}, and in the fourth $1{,}000^{\omega}$. Sometimes a fifth set of $\cdot 1^{\omega}$ each is added. In the figure will be seen 10 brass blocks surrounding a circular central one, with which they can be separately connected by a plug. The block partly hidden by the plug is numbered 0, and this block is connected to the centre of the next dial. Between each of these numbered blocks (except 9 and 0) one of the equal resistance coils is placed, and by means of the plug any number of them can be brought into circuit. For instance, if the block numbered 5 is so joined to the centre plate, the current passes from the plate by means of the plug, and through five of the coils round to the block number 0, which is joined to the next centre plate, or, in the case of the last dial, to a terminal screw. Some tests can be very quickly made with this form of bridge, and the result seen at a glance. Of course, the circuit is disconnected in the variable arm every time a plug is shifted, if only one plug is used for each dial.

FIG. 89.

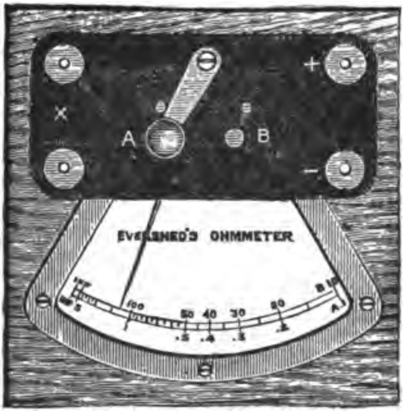


One of the most important uses to which the instruments and methods described in this chapter can be applied, is that of determining the 'insulation resistance' of an electrical circuit, which is accomplished by entirely disconnecting the remote ends of the conductors, and then measuring the resistance offered by the insulating material to the leakage of a current from one conductor to another, or to earth. Should this resistance fall below a certain prearranged standard, evidence will be afforded of the existence of a fault which requires to be localised and removed forthwith. The insulation of the conductors having been proved, the switches and other fittings may then be joined up, when a second careful test should be made, which in most cases will reveal the fact that the insulation resistance has fallen considerably, often as much as 50 per cent., due mainly to surface leakage. By testing the insulation resistance of the conductors separately, a ready means is afforded of determining whether a particular fault is in the covering of the wire, or in the fittings, and it may be observed that a certain amount of leakage at the fittings should be deemed of less importance than an equal or even a smaller leakage in the conductor covering; for whereas in the former case it is mostly due to moisture and therefore not liable to any serious increase, in the latter case it indicates a damaged or inferior insulating material, a fault which will most assuredly develop under the continued electrical stress.

In electric light installations very heavy currents and rather high E.M.F's. are frequently employed, which might cause serious damage to life and property should the insulation at any point be allowed to fall below a certain standard or become in any way faulty, and any such fault would, of course, also impair the efficiency of the lighting, to say nothing of the energy wasted. Similar conditions obtain with any system of electrical conductors and fittings for any purpose whatever, and it is necessary that some convenient means should be available for efficiently testing the whole installation, under conditions equally trying to the maximum stress which it will be called upon to sustain in practice. Especially must the source of electrical power employed for the test be able to develop an E.M.F. at least equal to the maximum intended to be used. otherwise there will be considerable risk that small incipient faults will not be shown up during the test, and will only become manifest when the circuit is in practical use, and when, therefore, the greatest inconvenience, and possibly damage also, will result.

As 100 volts is the lowest E.M.F. which generally obtains in practice, it is evident that the employment of batteries for testing would be exceedingly inconvenient, so much so, in fact that an efficient test is frequently shirked. A small magneto machine, such as we shall describe in a subsequent chapter, is far more convenient and portable, but it is hardly suitable for use with the apparatus ordinarily constructed for the measurement of resistance. Within the last few months an instrument has been introduced by Messrs. Goolden which answers admirably, and, in fact, is designed to work with such a machine. It is called an 'ohmmeter,' from the fact that its pointer indicates directly the number of ohms in the resistance under measurement. In practice, however, one does not actually require to find the exact resistance of an installation within a few ohms more or less. It is, indeed, sufficient if the apparatus can assure us whether, under the stress produced by a sufficiently high E.M.F., the insulation is above or below the standard, which we may here suppose to be fixed at 1 megohm (a million ohms). If below this standard, the circuit should be tested in sections until the fault is localised. The apparatus in question can promptly and decidedly indicate whether a resistance is above one megohm or below it, and supposing it to be above, of course the installation is passed as satisfactory. A top view of the instrument is given in fig. 90. When the small switch is placed as shown on the contact A, the outer scale A is to be used, but by shifting the switch to the contact B, a coil is shunted, thus enabling the lower resistances to be measured by readings on the inner scale, B. The wires from the source of E.M.F. (the magneto machine) are attached to the terminals marked + and —, while wires leading from the resistance to be measured are attached to the other terminals marked ×.

FIG. 90.



It is not possible to measure the higher resistances with certainty to within 100 ohms or so, but this is immaterial, as, if the insulation is below the standard, it matters little whether it is 700,000 or 700,200 ohms.

Fig. 91 is a view of the interior of the instrument turned upside down, the working parts there shown being placed under the ebonite slab on which the switch and terminals are fixed.

The scale plate is shown in fig. 90. The inner of the two scales is marked in divisions of 1,000 ohms from ten thousand up to infinity, while the outer reads in megohms from 0·1 megohm to infinity, the scale being fairly open up to 5 megohms. In the construction of the instrument there are three coils (shown in plan in fig. 92); two of them, *a a*, are placed with their planes parallel and are joined in series, while the third, *b*, is placed between and with its plane and magnetic axis at right angles to those of the coils *a a*. The inner coil, *b*, is shaped so as to allow the pointer to travel through a comparatively wide range. The figure, which is drawn from the under side, also shows the small steel needle in its zero position. This needle is then lying in the centre of the coil *b*, and along the common axis of the coils *a a*. In the case underneath it is placed a small weak bar magnet which adjusts itself so as always to neutralise the effect of the earth's magnetism, and, consequently, the only magnetic forces acting upon the needle are those due to the currents in the coils. A current passing through the coils *a a*, which are of high resistance, tends to keep the magnetic needle in the position shown, that is, at zero, with its length along the common axis of the coils *a a*. But its length is then parallel to the plane of the coil *b*, and any current

FIG. 91.

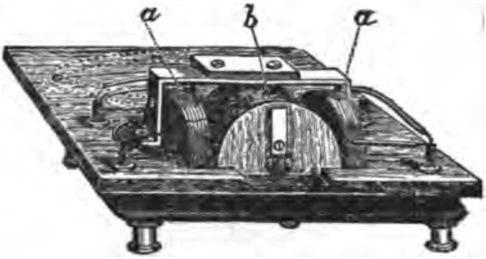
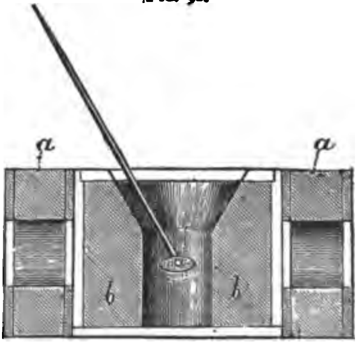


FIG. 92.



passing through this coil will deflect the needle more or less, its position of rest depending upon the relative strength of the currents in the magnetising coils and the deflecting coil. Now the coils *a a* are connected to the source of E.M.F. only, consequently the current in them, and the force with which the needle is urged to the zero position, is directly proportional to this E.M.F. The coil *b* is connected to the same source of E.M.F. but has the resistance to be measured joined in series with it ; this resistance is very high, and the current through *b* which tends to deflect the needle is inversely proportional to it. The deflection of the needle as indicated by the pointer is proportional to the E.M.F. and inversely proportional to the resistance ; but as the same source of electro-motive force is used for both branches of the circuit, any variation affects equally the deflecting and the magnetising currents, and, therefore, the deflection of the needle is simply inversely proportional to the resistance to be measured, that of the coil *b* being small.

When the resistance is infinite no current flows through the deflecting coil and the needle remains at zero, but as the resistance is lowered the deflection of the needle is proportionally increased, and it becomes a simple matter to calibrate the instrument so that the pointer shall indicate directly the value of the resistance in ohms or megohms. The ohmmeter, and the accompanying magneto machine which develops an E.M.F. of 120 volts, are enclosed each in a case of 5 inches cube, affording a very compact set for testing at the highest working pressure likely to be adopted in an ordinary installation.

CHAPTER VI.

MEASUREMENT OF ELECTRO-MOTIVE FORCE.

IN all classes of electrical work it is important to be able to accurately measure potential difference, or electro-motive force, and no better introduction to this branch of the subject can be obtained than that furnished by the study of the methods by which the electro-motive force of batteries can be compared. By Ohm's law we know that E = C R, where R is the total resistance of any circuit measured in ohms, C the current in amperes flowing through it, and E the electro-motive force in volts which maintains that current. So that, whenever the resistance and the current strength are known, the E.M.F. can be ascertained by multiplying these two quantities together. For instance, if a battery having a resistance of 15 ohms is joined up to send a current through a galvanometer of 320 ohms resistance, with a rheostat having 960 ohms unplugged, also in circuit, and if the resulting current is found to be 8 milliamperes, then the electro-motive force of that battery is C × R or ·008 × 1295 = 10·36 volts.

The measurement of current strength presents but little difficulty, but it is not often that the total resistance in the circuit is accurately known without measurement, and thus two tests at least are rendered necessary in order to ascertain the E.M.F. In practice it is usual to take some good constant cell or battery whose E.M.F. is known exactly and compare the unknown electro-motive forces with that of this 'Standard' cell or battery. As the accuracy of the results depends upon the accuracy of the value which is given to the E.M.F. of this standard, and upon its constancy, great care must be exercised in the choice and use of such a cell.

The best cell for a standard is that devised by Latimer Clark, which was described in Chapter III. If carefully used it will remain constant for years; but, as it polarises quickly, it should not be allowed to send so strong a current as even 1 milliampere, and, if possible, should only be used in those tests, to be presently described, in which the batteries are tested when they are not sending any current at all, but simply maintaining a potential difference. A rather serious drawback to this cell is, that its E.M.F. varies with a change of temperature, falling as the temperature rises; and although, the temperature being known, the variation of E.M.F. can be allowed for, such calculations are very inconvenient and take time. Its E.M.F. at 15° Centigrade is 1·435 volts.

The Daniell cell when in good condition does not polarise, even when developing a strong current, and it has the further advantage that a considerable variation of temperature makes little or no difference in its E.M.F. It is, therefore, a good standard for use in the workshop, and any form of Daniell cell in first-rate order may be employed, especially when the tests are independent of the battery resistance. But it must be remembered that the plates should be bright and clean, the supply of crystals in the copper cell plentiful, and the solution in the zinc cell half saturated. The E.M.F. then is 1·079 volts.

Since the current which a battery can develop is proportional to its E.M.F., it is evident that the E.M.F. of two batteries can be compared by observing the currents which they send through circuits offering *equal* resistances. The Daniell cell should be used as the standard in this case, and if it gives on a tangent galvanometer 25 divisions deflection through a total resistance of, say, 1,000$^{\omega}$, while another cell or battery gives 62·5 divisions through the same resistance, then

$$25 : 62{\cdot}5 :: E : x,$$

where E is the E.M.F. of the standard cell, and x that of the battery under measurement.

Therefore $$x = \frac{62{\cdot}5 \times 1{\cdot}079}{25} = 2{\cdot}7 \text{ volts nearly.}$$

One objection to this method is, that it is necessary to know the resistance of the batteries, in order that the total resistance may be made the same in both cases ; but if the resistance of the external circuit is comparatively high, then the resistance of the batteries may be ignored.

In this simple method, the resistance is kept constant, while the current varies The various currents are then measured and the relative E.M.F. deduced therefrom.

But it is also possible to compare electro-motive forces by varying the resistance and keeping the current constant, in which case the electro-motive force is proportional to the resistance ; for, the higher the E.M.F., the greater is the resistance through which it can send a given current. One great advantage in connection with this method is, that any kind of galvanometer which may be available can be employed, because the same deflection is produced in every case. In order, therefore, to compare the E.M.F. of any battery x, with the standard cell E, we should join up the standard cell in circuit with a rheostat and galvanometer, varying the resistance so as to obtain a convenient deflection of, say, 45°, and noting carefully the total resistance, R_1, in circuit. The battery to be tested should next be joined up, and the resistance altered, say, to R_2, so as to reproduce the deflection of 45°.

Then $$x : E :: R_2 : R_1 \text{ or } x = \frac{E R_2}{R_1}$$

In this test, too, the resistances of the standard cell, the battery, and the galvanometer must be known and taken into account unless the resistance in the rheostat is comparatively high, when these other resistances may be ignored.

But by a simple extension of this method, it is possible to obtain an accurate result without knowing either of these three resistances. The process consists in first joining up the standard cell, F in the same manner as in the previous test, and then adjusting the rheostat until a deflection of, say, 45° is obtained. The resistance should then be increased until the deflection falls to, say, 35°, noting carefully the exact number of ohms, P, by which the resistance is increased, in order to bring about the reduction in the deflection. The battery, whose electro-motive force, x, it is desired to measure, must now be substituted for the standard cell, and the resistance again adjusted until the deflection of 45° is reproduced. This resistance should then be increased by, say, Q ohms until the deflection is once more 35°. Then, as shown below,

$$x : E :: Q : P, \text{ or } x = E\frac{Q}{P} \text{ volts.}$$

To take an example. If with the Daniell cell as a standard the insertion of 720 ohms reduces the deflection 10°, that is to say, from 45° to 35°, and when the battery is substituted it is found necessary to add 2,300 ohms to reduce the deflection through the same 10°, then

$$x = 1{\cdot}079 \times \frac{2300}{720} = 3{\cdot}446 \text{ volts nearly.}$$

This is a very good method, and it is interesting and instructive to observe how the battery and galvanometer resistances are eliminated. This may be shown by Ohm's law as follows :—

Let G be the resistance of the galvanometer, r_1 the internal resistance of the standard cell, and R_1 the resistance in the rheostat when the needle is deflected through 45° by the current whose strength is indicated by C_1, then

$$C_1 = \frac{E}{R_1 + r_1 + G}.$$

Also let r_2 be the resistance of the battery whose E.M.F. is to be deduced, and R_2 the resistance in the rheostat necessary to reproduce the deflection of 45°, or when the current strength can again be indicated by C_1, then

$$C_1 = \frac{x}{R_2 + r_2 + G},$$

therefore
$$\frac{E}{R_1 + r_1 + G} = \frac{x}{R_2 + r_2 + G}.$$

$$E(R_2 + r_2 + G) = x(R_1 + r_1 + G) \quad . \quad . \quad . \quad . \quad (1).$$

When the resistances R_1 and R_2 are increased by P and Q respectively to obtain the deflection of 35° which will correspond to a current strength which can be called C_2, then

$$C_2 = \frac{E}{R_1 + r_1 + G + P} = \frac{x}{R_2 + r_2 + G + Q},$$

therefore
$$E(R_2 + r_2 + G) + EQ = x(R_1 + r_1 + G) + xP. \quad (2).$$

Subtracting equation (1) from (2) we get

$$E\,Q = x\,P,$$

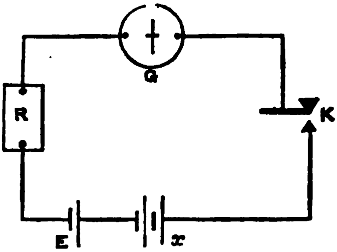
therefore

$$x = E\,\frac{Q}{P}.$$

To ensure accurate results it is essential that the galvanometer for this test should be sufficiently sensitive to indicate a very slight alteration in the current strength, and, if possible, the resistances P and Q should be as high as or even higher than the total resistance in the circuit prior to their insertion.

There is another good method which is sometimes very convenient because it is not necessary to know or ascertain the actual resistance of any portion of the apparatus, whether it be the galvanometer, the rheostat, or the battery, these being the appliances required for the test. As in the previous tests, we may denote the E.M.F. of the standard cell by E, and that of the battery to be measured by x. The standard cell E and battery x are joined up in series, so that they assist each other in sending a current through a rheostat or set of resistance coils, R, and a tangent galvanometer, G (fig. 93), and the resistance adjusted until a fairly high deflection, say, sixty-five tangent divisions, is obtained. Then, on reversing the standard cell (supposing it to be of lower E.M.F. than x) so that the two E.M.F.'s, x and E, are opposed to each other, the resulting current will manifestly be due to the *difference* between the two E.M.F.'s, and, as the total resistance remains unaltered, the current and the deflection produced by it will be diminished, say, to twenty-five divisions. Then, denoting the first deflection (sixty-five divisions) due to both E.M.F.'s by D, and the second deflection (twenty-five divisions), due to the *difference* between the two E.M.F.'s when opposed, by d,

Fig. 93.



$$x : E :: D + d : D - d,$$

or

$$x = E\,\frac{D + d}{D - d}.$$

Inserting the values as above, we get

$$x = 1{\cdot}079 \times \frac{65 + 25}{65 - 25} = 2{\cdot}428 \text{ volts nearly.}$$

The object of reversing the battery or cell of lower E.M.F. is to obtain both deflections on the same side of the zero point. Were the battery of higher E.M.F. to be reversed, it would cause the needle to be deflected to the opposite side of the zero, and if the pointer happened to be bent it would cause an incorrect calculation.

If, when joined up in opposition, no deflection is obtained, then the electro-motive force of the standard cell will be the same as that of the battery under test, or $E = x$. The only objection to the method is that in the first case the weaker battery, which is usually the standard cell, has a rather strong current flowing through it which may lower its E.M.F., while, when joined in opposition, the current is passing in the opposite direction and will almost certainly cause a slight increase in its E.M.F. In order to eliminate as much as possible this source of error, it is advisable to introduce a 'key' or contact-maker to open and close the circuit at will, as shown in fig. 93. By the skilful manipulation of this key the needle can be brought to rest immediately without a single oscillation, and the deflection then read before any appreciable alteration of the E.M.F. can take place. As a further precaution, the resistance in circuit should be made as high as possible so as to reduce the strength of the current. By such means the objection becomes almost entirely obviated. To admit of high resistance being placed in the circuit, the 320^{ω} coil of the galvanometer should be used unshunted, and the magnet placed rather low down with its north pole pointing northwards, so that it will act in opposition to the earth's magnetism.

That the resistance of batteries and galvanometer need not be known or ascertained is evident from the fact that they form part of the constant total resistance, which is the same in each case and which does not enter into the calculation. This may be shown algebraically, for if we let R indicate the total resistance in circuit, (including batteries and galvanometer), c_1 the current in the first case giving deflection D, and C_2, the weaker current, giving deflection d, then

$$C_1 = \frac{x + E}{R}, \text{ or } R = \frac{x + E}{C_1},$$

and
$$C_2 = \frac{x - E}{R}, \text{ or } R = \frac{x - E}{C_2}.$$

Therefore $\frac{x + E}{C_1} = \frac{x - E}{C_2}$, or, since the currents are proportional to the deflections in tangent divisions, $\frac{x + E}{D} = \frac{x - E}{d}$.

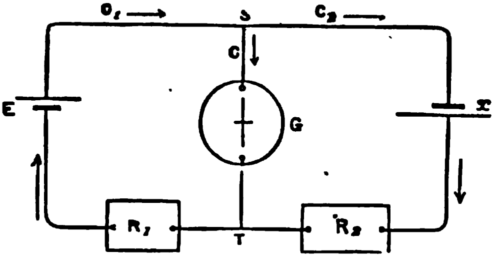
Whence
$$D x - D E = d x + d E,$$
$$x(D - d) = E(D + d),$$
$$x = E \frac{D + d}{D - d}.$$

It will doubtless be remembered that, if the poles of a battery are joined by a short piece of thick wire having practically no resistance, the current flowing through the circuit will depend simply upon the E.M.F. of the battery and its internal resistance. Now, the thick wire coils of the tangent galvanometer which we have described are of very low resistance, and may be used for the measurement of the current which a battery can give under these conditions. Thus, supposing a battery of twenty Daniell cells, having a resistance of 5 ohms per cell, were joined up to send a current through one of the low resistance coils of the tangent galvanometer, the current flowing would be $\frac{20 \times 1{\cdot}079}{20 \times 5} = {\cdot}2158$ of an ampere, and the current from one cell, or 100 similar cells, should be the same, because when the E.M.F. is increased by increasing the number of cells, the internal resistance—that is, the total resistance in circuit—is increased in the same proportion. A galvanometer with a very low resistance coil affords, therefore, a means of rapidly testing the *condition* of a number of similar batteries, for the deflection of the needle will be decreased if either the internal resistance of any cell is above or the E.M.F. of any cell below the standard. It is, then, only necessary to ascertain the deflection given by a cell or a battery known to be in good condition, and adopt this as the standard. Then if a battery, say, of ten cells gives a current equal to that of the standard cell, it may be fairly concluded that the battery is in good condition, but if a second similar battery gives a deflection of seven or eight degrees less, then the conclusion is that there is something wrong with it; its resistance is too high or its E.M.F. too low. The matter may be quickly decided by joining up the faulty battery in opposition with the similar battery known to be good—that is to say, joining their copper or positive poles together and their zinc or negative poles to the galvanometer. If they then give no deflection, we know that their electro-motive forces are equal, and the fault is proved to be one of high resistance. If, on the other hand, a current is produced, there must be a difference in E.M.F., and the fact that the suspected battery is the faulty one would be demonstrated if the direction of deflection were such as to prove that the other is urging a current through it.

But galvanometers with short thick wire coils having but a few convolutions are only affected by very powerful currents, and are only used where it is essential that the introduction of the instrument into any circuit should have no appreciable effect upon the strength of the current flowing through it. When this restriction is not imposed increased accuracy can usually be obtained by employing a more delicate instrument, in which a coil of many turns, and generally of fine wire offering a high resistance, is employed; because, although the current through the galvanometer is weakened by the added resistance, the effect is more than balanced by the increased number of times which the current travels round the needle. In fact, the flow of a very feeble current through such an instrument, or the maintenance of a very low difference of potential at its terminals, may suffice to produce a good deflection, while under similar conditions a galvanometer with a thick wire coil would be unaffected. It was observed, when considering the Wheatstone bridge method of measuring resistances (Chapter V.), that one great advantage pertaining to it is, that in making the final adjustment only a very weak current or no current at all passes through the galvanometer. It is therefore practicable in such cases to use a very delicate instrument, and, in order to prevent damage being done to the needle or its pivot, or to prevent the coils being fused by the passage of a heavy current, the coil can be shunted until the adjustments are almost completed.

It will also be remembered that the instrument need not be of any particular design, since the final result is obtained with the needle undeflected; a galvanometer such as this can also be employed in several methods which have been devised for the comparison of electro-motive forces, in which the instrument is simply used to denote the *absence* of a current, and in which, therefore, the consequent advantages are the same as in the case of the Wheatstone bridge. Fig. 94 shows the connections for one such method.

FIG. 94.



E is the standard cell and x the battery whose E.M.F. is to be measured. R_1 R_2 are two sets of resistance coils, and G is a delicate galvanometer. A certain resistance is introduced into the circuit by unplugging the necessary coils in R_1, and the resistance in R_2 is adjusted until the current ceases to pass through the galvanometer, thus showing that the two points, S and T, have been brought to the same potential. This being the case, then

$$x : E :: R_2 : R_1,$$

therefore

$$x = E \frac{R_2}{R_1}.$$

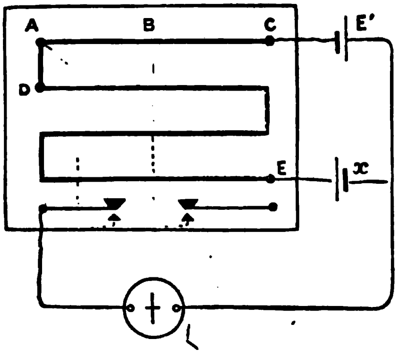
As an example, suppose the Latimer Clark cell to be used as a standard, and R_1 fixed at 1,000 ohms, while the potentials at S and T are equalised by making R_2 5,650 ohms, then

$$x = 1{\cdot}435 \times \frac{5650}{1000} = 1{\cdot}435 \times 5{\cdot}65 = 8{\cdot}108 \text{ volts.}$$

It will be observed that the working out of this example is simplified on account of R_1 being made 1,000 ohms. For this reason it is preferable to always make the resistance in the same arm as the standard cell some multiple of 10, and obtain a balance by adjusting the other set of coils.

The horizontal galvanometer designed for use with the Wheatstone bridge answers very well for this test, and, as will be seen from fig. 95, the bridge itself may be used for the two sets of coils and then the usual key can be employed in the galvanometer circuit, while the 'infinity' plug between A and D can be used to break the battery circuit and so minimise any error due to polarisation.

FIG. 95.



When a delicate galvanometer is not available, R_1 and R_2 must be lower, but then the battery resistances become important and cannot be ignored. They may, however, be eliminated by increasing one of the resistances, say R_1, by a certain amount, say P ohms, and obtaining a balance again by increasing R_2 by Q ohms. Then

$$x : E :: Q : P,$$

therefore

$$x = E \frac{Q}{P}.$$

The electro-motive forces are, in fact, simply proportional to the increase of the original resistances R_1 and R_2.

For example, if after one balance had been obtained, we were to increase the resistance R_1 by 500 ohms, and again obtain a balance by adding 2,852 ohms to R_2; then $P = 500$ and $Q = 2852$, therefore

$$x = 1{\cdot}435 \times \frac{2852}{500} = 8{\cdot}185 \text{ volts.}$$

The proof of the method depends upon two laws demonstrated by Kirchhoff, which we will endeavour to explain.

Let the resistance R_1 be slightly reduced, so that the balance is upset, then the currents in the three arms will flow in the direction indicated by the arrows in fig. 94.

The first of Kirchhoff's laws (which is almost self-evident in the present simple case), states that the current flowing to the point S is equal to the sum of the currents flowing from it, that is,

$$C_1 = C_2 + C \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1).$$

The second law declares that in any complete circuit, even when it forms part of a network, as R_1 E S T, the sum of the products of the current strength in each arm into the resistance of that arm is equal to the sum of all the electro-motive forces in the circuit. That is to say, if in each arm or portion of the circuit the individual resistance of that arm is multiplied by the strength of the current flowing through that resistance, and if all the products so obtained are added together, then the sum so produced will be exactly equal to the sum obtained by adding together all the electro-motive forces in the various arms of the circuit.

The *algebraical* sum must, of course, be taken; for instance, if two currents, or two E.M.F.'s, are opposite in direction, one must be reckoned as *plus* and the other as *minus*.

In the circuit R_1 E S T the only E.M.F. is that of the standard cell, which we denote by E, and, neglecting the internal resistance of this cell, we form the second equation thus:

$$E = C_1 R_1 + C G \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2),$$

G being the resistance of the galvanometer.

Similarly, in the circuit R_2 x S T, the only E.M.F. is x, but the currents in the two arms are in opposite directions. Therefore

$$x = C_2 R_2 - C G \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3).$$

By inserting in (2) the value of C_1, given in (1), we get

$$E = (C_2 + C) R_1 + C G,$$

that is,

$$E = C_2 R_1 + C R_1 + C G \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4).$$

From (3),

$$C_2 = \frac{C G + x}{R_2};$$

and, inserting this value for C_2 in (4), we get

$$E = \frac{R_1 (C G + x)}{R_2} + C R_1 + C G;$$

$$R_2 E = C R_1 G + R_1 x + C R_1 R_2 + C G R_2$$

therefore
$$C = \frac{R_2 E - R_1 x}{R_1 G + R_1 R_2 + R_2 G} \quad \text{(5).}$$

This equation gives us the value of the current flowing in the galvanometer circuit when the balance is upset, in terms of the various electro-motive forces and resistances. But in making the test we adjust so that no current flows through the galvanometer; therefore, when a balance has been obtained, $C = 0$, and, consequently, the fraction which forms the right-hand side of equation (5) is equal to 0.

Therefore, the numerator of the fraction

$$R_2 E - R_1 x = 0,$$

that is,
$$R_2 E = R_1 x, \quad \text{(6).}$$

and
$$x = E\frac{R_2}{R_1},$$

which proves the case when the battery resistances are so small as to be negligible.

Equation (6) holds good, in fact, so long as R_1 and R_2 represent the total resistance in their respective arms of the system.

When the resistances of the batteries cannot be ignored, they must be added to R_1 and R_2 respectively to make up the total resistance in the arm, and then equation (6) becomes

$$E(R_2 + r_2) = x(R_1 + r_1), \quad \text{(7).}$$

where r_1 is the resistance of the standard cell, and r_2 that of the battery under test. Also, when R_1 is increased by P ohms, and R_2 by Q ohms,

$$E(R_2 + r_2 + Q) = x(R_1 + r_1 + P)$$

that is,
$$E(R_2 + r_2) + E Q = x(R_1 + r_1) + x P \quad \text{(8).}$$

Subtracting (7) from (8), we obtain

$$E Q = x P;$$

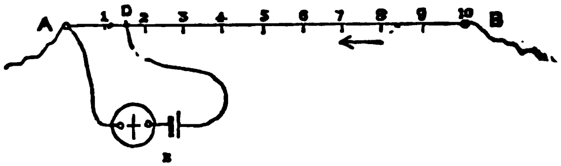
therefore
$$x = E\frac{Q}{P}.$$

There are a number of very beautiful methods for the comparison of electro-motive forces, somewhat similar in principle to those just described. We have selected a few and worked them out at length, not only because they are in themselves interesting, but also because they involve, in a rather simple form, some very important principles and laws which the student will do well to master.

We will now direct our attention to a method based upon a somewhat different principle. In this case, again, no current passes through the galvanometer when the final adjustment has been made, thus permitting the use of a delicate instrument. But a further very great point in its favour is the fact that the batteries do not send any current while their E.M.F.'s are being actually compared. Consequently, the Latimer Clark cell may be used as a standard to the best advantage, and the true E.M.F. of a battery subject to polarisation, like the Leclanché, can easily be measured; and further, since no current flows through the batteries or the galvanometer in the battery circuit, their resistances have no effect whatever, and therefore need not be known.

If between the ends A and B (fig. 96) of a uniform German-silver wire one metre (39·37 inches or 1,000 millimetres) in length a potential difference of 10 volts is maintained, the fall of potential will be uniform, say, from B to A. Now it must be possible, under such conditions, to find a point in the wire such that the potential difference between that point and the end A shall be any desired fraction of 10 volts. For instance, between A and the middle of the wire, C, the difference is 5 volts. Furthermore, if the negative pole of the Clark standard cell E is joined to the point A, it will assume the same potential as that point, while the end of the wire connected to the positive pole will be 1·435 volts above that potential. A galvanometer may be joined up on either side of E without affecting the final result, and if the free end of the wire is joined to any point near B a current will flow through the galvanometer G in opposition to the standard cell, because the potential of the point near B is more than 1·435 volts above that at A; while

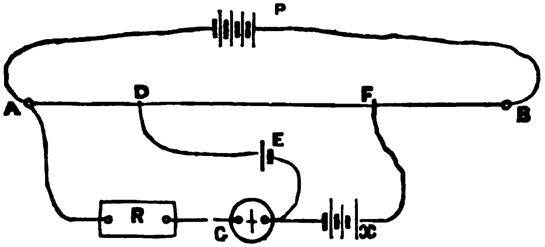
FIG. 96.



on the other hand, if contact is made at a point very near to A, where the potential is less than 1·435 volts, the standard cell will be able to maintain a current through the galvanometer and deflect the needle in the direction opposite to that which resulted from making contact at the point near B. Now, between these two positions a point, D, may be found where the needle will be undeflected, showing that no current is passing in either direction through the standard cell and galvanometer, and this point will be such that the difference of potential between it and A is equal to the maximum difference of potential which the standard cell can produce, viz. its E.M.F. of 1·435 volts. Since each of the ten equal parts into which the wire is divided represents a potential difference of one volt, the point D, at which a balance is obtained with the standard cell, should be nearly midway between 1 and 2. If the wire is perfectly uniform in resistance the fall of potential will also be perfectly uniform, and the exact position of the balancing-point would then be 143·5 millimetres from A. This shows the advantage of having a wire one metre in length divided into millimetres. As another example, suppose the standard cell were replaced by a battery of unknown E.M.F., we could readily find its E.M.F. by making contact at different points along A B until the absence of a current through the galvanometer indicated that a point had been touched where the E.M.F. is balanced. If this point were 970 millimetres from A, then the E.M.F. of the battery would be 9·7 volts. We have remarked that the resistance of the galvanometer and battery may be high and yet not affect the final result. The only objection to high resistance is that when the balance is nearly, but not quite, obtained, the potential difference tending to send a current through the galvanometer is very small, and if the resistance in the galvanometer circuit is very high the resulting current will be weak and may not be able to affect the galvanometer. This would prevent the balancing-point being found exactly, and it is a good plan, in order to avoid such want of sensitiveness, to employ a very delicate galvanometer, and place a set of high resistance coils in circuit with it. At first, all the resistance should be unplugged; it can then be reduced as the adjustment becomes approximately correct, the final adjustment being made with all the resistance out of circuit. Injury to the galvanometer may thus be avoided, and the greatest possible degree of accuracy attained.

It is clear that if we could with certainty maintain a constant potential difference between the extremities of the graduated wire, no standard cell would be required, and it would be very convenient to be able to measure E.M.F.'s as simply proportional to a certain length of the wire. It is difficult, however, to maintain any given difference of potential between two points for any length of time, and therefore in practice a slightly different arrangement to that just described is adopted. A current is sent through the wire A B (see fig. 97) from some fairly constant generator, P, such as a good low-resistance battery or a few of the 'secondary cells' to be described hereafter, sufficient to maintain between A and B a potential difference greater than that of the highest E.M.F. to be measured. The wire is stretched over a scale divided into a thousand parts, and therefore, if of uniform gauge and material, the fall of potential along one of these units is equal to a thousandth part of the fall along the whole wire. The Clark cell, E, and the battery to be measured, x, are joined up with their negative poles connected through a galvanometer, G, and a set of coils, R, to the point A, as shown in fig. 97. Their other poles are connected to sliders, by means of which contact may be quickly made with any point along the wire. The whole of the resistance is put in circuit at first, and the slider connected to the standard battery is shifted along until a point is found where the deflection on the galvanometer is very slight when contact is made with the wire A B. The resistance R is then gradually reduced until the exact point (D) is found. The distance from A to D must be carefully noted, and

FIG. 97.



then a point, F, at which the E.M.F. of the battery x is balanced, is found in a similar manner. Now, the potential difference between A and D is equal to the E.M.F. of the standard cell—that is, 1·435 volts—and the potential difference between A and F is equal to the E.M.F. of the battery x. Therefore

$$\text{AD} : \text{AF} :: \text{E} : x.$$

Suppose A D to be 120, and A F 685, divisions; then

$$120 : 685 :: 1·435 : x;$$

therefore $$x = \frac{685 \times 1·435}{120} = 8·19 \text{ volts.}$$

It will thus be seen that it is unnecessary to maintain any particular potential difference per unit of length of the wire, for this can be immediately found by means of the standard cell. But it is advisable, after the adjustments have been made as above, to verify the result by making contact with both sliders at almost the same moment, in order to ascertain whether or not the fall of potential has varied during the test.

In fact, one great feature in favour of this arrangement is that the test may so be made that a slight variation of the potential difference at the ends of the stretched wire need not cause any error; the source of inaccuracy which has most to be guarded against is a want of uniformity in the wire itself. By using a *low* resistance battery a greater proportion of the fall of potential takes place in the external circuit—that is, along the stretched wire—than when a high resistance battery is employed; hence the suitability of secondary cells for this purpose. A greater length of wire may be conveniently obtained by stretching it backwards and forwards several times upon a board. An instrument based upon the foregoing principles for measuring potential differences is commonly called a potentiometer. The wire is sometimes wound in a spiral groove round an ebonite cylinder, and, when made in this form, it can easily be divided into 20,000 parts, but this type is rarely used for practical work.

In all the preceding methods potential difference is measured indirectly or by comparison. Instruments have, however, been devised which indicate directly, in volts, the difference of potential between any two points; such instruments are called voltmeters.

That invented by Major Cardew is very reliable, and it is at the same time simple in principle. If a wire is heated it increases in length. This linear expansion or extension is proportional to the product of the rise in temperature and the coefficient of expansion for the particular wire. The coefficient of linear expansion is defined as the elongation of a body of unit length when its temperature rises from zero to one degree (Centigrade), and this coefficient or proportional extension for platinum is 0·0000088, so that, for an increase in temperature of 10° C., a yard of platinum wire would be extended to 1·000088 yards. By measuring the amount of extension produced by heating a wire, the increased temperature can therefore be inferred. Now, when a current of electricity passes through a wire it performs a certain amount of work in overcoming its resistance, and the generation of heat is the result.

The rise in temperature resulting from the generation of a certain amount of heat does not, however, bear a simple ratio to that amount of heat. It depends, in fact, upon the time or duration of the current and the specific heat or calorific capacity of the particular substance. The former of these factors is so exceedingly apparent that we need not further enlarge upon it. The specific heat of a body is defined as that quantity of heat which it absorbs when its temperature rises through a given range—say from zero to 1° C.—as compared with the quantity of heat which would be absorbed by an equal mass of water when its temperature is exalted through the same range. If, for example, a pound of mercury at 100° C. is mixed with, or placed in, a pound of water at zero, the temperature of the mixture will only be 3° C., so that, while the mercury has lost 97°, the equal mass of water has only increased 3°, or, in simple language, a quantity of water absorbs about thirty-two times as much heat as an equal weight of mercury, in undergoing the same exaltation of temperature. The specific heat of water being taken as unity, that of mercury is therefore 0·03332. Similarly, the specific heat of platinum is 0·03244.

The variation in the temperature of a wire due to an increment or decrement of heat, depends also upon its weight or its sectional area, for it will be evident that if two wires of similar material and of equal resistance, but of different gauge or different weight –

such, for example, as a given length of platinum wire weighing one gramme, and another platinum wire, twice as long, but weighing four grammes (offering, therefore, equal resistances)—have the same current passed through them, they will not be raised to the same temperature, although the amount of heat actually developed will be the same in each case. This follows from the fact that in the one case there is more material to heat than in the other.

When a current of electricity passes through a wire, and performs a certain amount of work in overcoming its resistance, the equivalent of the quantity of energy absorbed in the performance of this work is seen in the development of a definite amount of heat which is imparted to the wire. The heat (H) developed in a unit of time is, in fact, directly proportional to the amount of power expended in overcoming the resistance of the conductor—that is to say, it is proportional to the product of the difference of potential, E, between its extremities, into the strength of the current C, which is maintained through it, or $H : E\,C$. If the resistance of the wire remains constant, the value of C varies directly as E; by doubling E, C is also doubled, and the heat developed then varies as the square of E.

Again, the heat unit is defined as that amount of heat which is required to raise 1 gramme of water through 1° C. in temperature, and a potential difference of 1 volt maintained through a resistance of 1 ohm develops 0·24 such heat units per second—that is to say, the number of heat units, H, developed in t seconds, is

$$H = 0{\cdot}24 \times E\,C\,t.$$

As $E = C\,R$, it follows that $E\,C = C^2\,R$, so that the formula may also be expressed by saying that

$$H = 0{\cdot}24 \times C^2\,R\,t.$$

Collecting all these facts into one simple formula, where T° represents the rise in temperature in Centigrade degrees, E the potential difference in volts, C the current strength in amperes, t the time in seconds, h the specific heat, g the weight of the metal in grammes, and 0·24 the constant which, as pointed out above, is necessary to obtain a result on the Centigrade scale, we may say that

$$T^\circ = 0{\cdot}24 \times \frac{E\,C\,t}{g\,h} = 0{\cdot}24 \times \frac{C^2 R\,t}{g\,h},$$

so that a current of one ampere, flowing for one second through 1 gramme of water (whose specific heat is 1·0), and offering 1 ohm resistance, involving, therefore, a potential difference of 1 volt, would, if all the energy expended were devoted to the generation of heat, be raised 0·24° C. in temperature.

Similarly, if the same current were maintained through a platinum wire of the same weight and resistance, the increase of temperature would be

$$T^\circ = 0{\cdot}24 \times \frac{E\,C\,t}{g\,h} = 0{\cdot}24 \times \frac{1 \times 1 \times 1}{1 \times 0{\cdot}03244} = 0{\cdot}24 \times \frac{1}{0{\cdot}03244}$$
$$= 7{\cdot}4^\circ \text{ C., nearly.}$$

In the Cardew voltmeter a length of very fine platinum-silver wire is employed, and is heated by the passage of the currents whose E.M.F. it is desired to test. In each test, therefore, g and h retain the same values, and by limiting the increase of temperature to a few degrees, the very slight variation of R becomes a negligible quantity. Similarly, by employing a fine wire, it speedily rises to such a temperature that, with any given current, the loss of heat due to radiation equals in amount that which is developed by the current. The only really variable quantities, therefore, are E and C. But, as already pointed out, C varies uniformly with E, and if the facilities for radiation remain the same, the increase of temperature, and with it the elongation, will always be the same for any given value of E. Hence, the amount of elongation can be made to indicate the potential difference maintained between the extremities of the wire.

Simple as the principle is, the construction of a reliable practical instrument is a matter of some difficulty, and an enormous amount of experimental work has been performed in determining the exact sources of error to which a Cardew voltmeter is liable. Fig. 98 illustrates the form of this instrument adopted by Messrs. Goolden after an exhaustive series of experiments extending over a number of years, and in it the inherent sources of variation and error are practically eliminated. The outer casing is removed to show the essential parts as viewed from the back.

The platinum-silver wire is 0·0025 inch (2½ mils) in diameter, and is fixed at one end to the small brass block *m*. Thence it

FIG. 98.

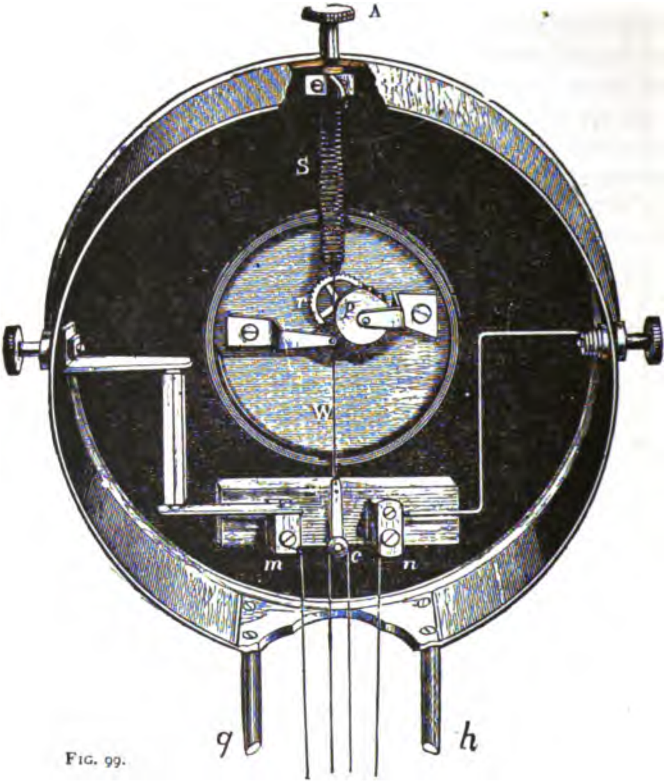
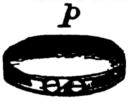
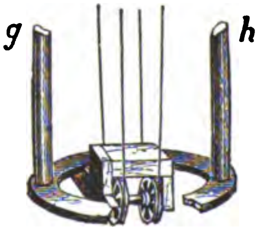


FIG. 99.





is led round one of two grooved pulleys supported by a ring at the ends of two metal rods, *g h*, which are about 36 inches long, and are fixed to the brass base-plate. From this pulley the wire returns, and is passed round a small pulley, *c*; thence it is led to the second pulley at the top of the rods, and is finally terminated at the small brass block *n*. The brass pieces *m* and *n* are supported by the insulating block of varnished vulcanised fibre, which is securely fastened to the brass base-plate, and *m* and *n* are connected each to one of the main terminals of the instrument, which are insulated by ebonite or fibre collars from the brass casing. The wire should pass round the pulleys at the top of the rods in such a manner that a pull at *c* on the two centre wires would cause both pulleys to rotate in the same direction, and, the spindle being pivoted in jewelled holes, the friction is reduced to a minimum.

The small part, *c*, referred to as a pulley, only acts as such during the wiring of the instrument, as the extension of the wire when the apparatus is subsequently used does not cause it to rotate. It is made of vulcanised fibre, with a small groove round its circumference in which the wire lies, and is fixed by a small screw passing loosely through its centre to one end of the thin brass strip T, the other end of which has attached to it a fine platinum-silver wire, W, connected to the spiral spring S. The tension of this spring, which can be varied by means of the adjusting screw A, keeps the wires taut, and when the main terminals are connected to points in a circuit at different potentials, a current passes—say to the block *m* - up the wire, and round the first pulley back to the insulating reel, *c*; thence, again, to the top of the instrument, round the second pulley, and back by way of *n* to the other terminal. This current heats the wire, which expands, and the slack is immediately taken up by the spiral spring S, so that the small brass strip T and the wire W are moved through a distance equal to the expansion of *two* lengths of the heated wire. The amount of expansion (and therefore of the potential difference applied) is measured by observing the distance through which the length of wire W is moved; but as this distance is, at the most, extremely small, some mechanical multiplying arrangement is necessary, and, since the force producing the movement is also very feeble, great care must be exercised in avoiding the introduction of any appreciable friction. This result is attained by the use of a jewelled watch movement. The wire W is led round a small pulley, *p*, fixed upon the same spindle as a toothed wheel, *r*, which gears into a small pinion, the spindle of which carries a long needle or pointer, passing over a scale plate at the back of, and not visible in, the figure. When the wire is extended by the current, the spring S causes the pulley *p* to turn through a small angle, and with it also the wheel *r*, the pinion, and the pointer; and, as the diameter of the wheel is much greater than that of the pinion, the pointer is turned through a large angle by a comparatively small extension of the wire

The passing of the wire W round the pulley so as to get a reliable grip, and at the same time avoid friction or risk of damage to the fine wire, is a more difficult matter than might at first sight appear, and, like every other detail, has received much study before the method now employed was finally adopted.

The pulley is shown separately in fig. 99. It has two narrow parallel grooves round its circumference, at one part of which (where it is filed away flat) two set-screws are fixed, both screwed up home. The wire is led from T round the first groove to the screw-heads, between which it passes over to the second groove, in which it completes its journey round the pulley, and is then led to the spiral spring.

The wire is so fine that it would not bear being pinched under the screw-heads, but the arrangement described effectually overcomes any tendency to slip; and as the pulley only moves through a small angle, never making a complete revolution, no sensible friction is introduced. Insignificant as this detail may appear, it is, as already indicated, very important, and the same remark applies to the shape of the spiral spring S and to the material of which it is composed. The gradual alteration of this spring was found to be the main cause of the slight variation from zero which was frequently observed in the earlier instruments. It is necessary that the tension of this spring should remain constant; and the difficulty has been surmounted by (*a*) choosing a spring least liable to vary, spiral in form and of German silver, and (*b*) providing a thumbscrew A on the outside of the case, by turning which the pointer can be readily restored to zero should it become necessary

Although there are four straight lengths of wire equally heated, it will be remembered that the expansion measured is only equal to that of two lengths, for, since *c* does not rotate, its movement would be the same if one of the wires were rigidly fixed to it and the other removed. But it will be noticed that the tension due to the spiral spring is equally distributed between the two wires leading from *c*, and this affords the great advantage that double the tension can be given to the spring, which means that the force with which the pulley *p* is turned can be doubled, and any slight error due to friction correspondingly reduced, without, at the same time, necessitating the adoption of a comparatively thick wire. The wheel work is well made, but it is of course impossible to altogether avoid 'back-lash'— that is to say, as the teeth of the driving-wheel do not fit tight between the teeth of the pinion, the latter does not begin to move absolutely at the same moment that the driving-wheel does when its motion is reversed. To avoid the slight error which this might cause, a hair-spring is fixed to the pinion spindle. This spring is visible in fig. 98, the pinion being immediately behind and therefore hidden by it. It is adjusted so as to maintain sufficient pressure between the teeth of the wheel and pinion to keep them always in contact, so that in either direction the two move simultaneously.

The whole of the casing is of brass, wood, from its liability to warp, being wholly unsuitable ; but it is clear that the rods (*g h*, fig. 98) cannot be made of that metal, as, its coefficient of expansion being higher than that of platinum silver, it would expand more than the wire with any rise of temperature, atmospheric or otherwise, and cause a deflection of the pointer. On account of the expense, platinum-silver cannot be employed for this purpose. Iron has, however, a lower coefficient of expansion than the wire, and the rods are therefore made partly of iron and partly of brass, the length of these parts being so proportioned that the greater expansion or contraction of the brass shall be neutralised by the lesser expansion or contraction of the iron, and the whole rod vary in length in exactly the same proportion as the wire itself. The wires are encased throughout their length by a brass tube which can easily be removed, and the arrangement of the pulleys, together with an opening in the supporting ring to which they are attached, facilitates the re-wiring of the instrument. In order to prevent damage to the working wire by the accidental passage of a too powerful current, a safety fuse is inserted in series with it, consisting of a short length of platinum-silver wire, 0·0014 inch ($1\frac{2}{5}$ mils) in diameter, which fuses and breaks the circuit before the current attains sufficient strength to fuse the thicker working wire. This fuse-wire is placed in a slit along the face of a rectangular strip of vulcanised fibre, each end being terminated at a round-headed brass screw in the end of the block, which is firmly held between two flat springs making contact with the screw-heads, one spring being connected to *m* and the other to the left-hand terminal. Several such-fuse-wire blocks can be kept at hand, and the replacing of a fuse is then but the work of a moment. Connection between *n* and the other terminal is made by a stout, stiff wire.

This type of instrument, in which the wires are supported by the two compound rods, and in which the tube slipped over them simply acts as a casing to protect the wires from air currents and damage, is designed for use with the tube in a vertical position, the end at which the pulleys are fixed being placed uppermost. Now, as soon as the wire gets hot, it heats the adjacent air, which, being displaced by colder air, rises, and consequently currents are set circulating in the tube. The result is that when the pointer is deflected a slight oscillation may be observed, sufficient to prevent the value of the potential difference being read with certainty to within half a volt. This oscillation can be entirely eliminated by simply placing the tube in a horizontal position, for the whole length of the wire then lies in a more evenly heated atmosphere, in which such air currents as rise from it are feebler and more uniform in their distribution in relation to the wire.

A more accurate, though more expensive, instrument is made by dispensing with the rods and fixing the jewelled pulley bearings in the end of the tube itself, which, of course, is then compounded, being made of brass and iron in the necessary proportions. Such instruments are pre-eminently adapted for experimental work, on account of their extreme accuracy, and are, of course, always employed in the horizontal position. The rod pattern (which can also be used horizontally) is, however, a first-rate piece of apparatus for the engine-room or workshop, where a possible error of half a volt in the reading is a matter of little moment, and it has the advantage that the working wire can be more easily replaced than in the tube form. The voltmeter illustrated is capable of measuring from 30 to 120 volts. The calibration is carefully performed, the wire being continually heated by the passage of a current, and stretched, for some days previously, to bring it to its normal condition. As it is the heating of the wire which affords a measure of the electro-motive force, the 'heating-error' peculiar to most voltmeters is here entirely absent, and the instrument may be, and in fact is, kept continually connected up for days and weeks together. For the same reason, the reading is unaffected by the presence of external currents or any electro-magnetic field, and, as iron is not employed and the wire is not coiled, its self-induction is practically *nil*. Hence, alternating potential differences can be measured; but it must be remembered that this same absence of self-induction in the instrument, in allowing a current to rise suddenly to its full value, limits the range through which the fuse can protect the working wire; for, although the fuse acts with certainty if the current rises at all gradually, a very sudden application of a very high E.M.F. would develop a heavy current instantaneously, fuse and wire being melted simultaneously.

FIG. 100.

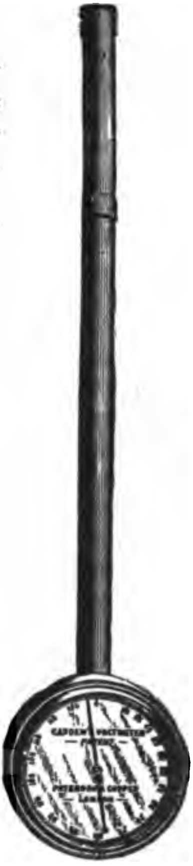
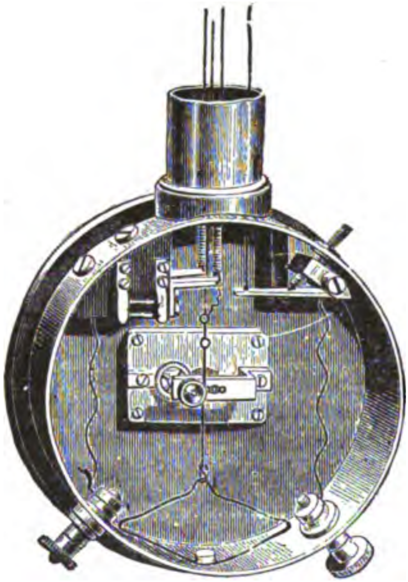


Fig. 100 is a general view of the Cardew voltmeter as made by Messrs. Paterson & Cooper, the internal portion of the apparatus, as viewed from the rear, being shown in fig. 101. The instrument consists of a long piece of platinum-silver wire, 0·0025 inch in diameter, and passing up and down the long tube over frictionless pulleys supported by the tube. One end of the wire is rigidly fixed, the other end being attached to a silk thread which passes round a small spindle and is kept stretched by means of the wire bow-spring shown in the lower portion of the figure. The wire, therefore, which would otherwise sag or slacken on being heated, is kept taut, acting and reacting with the spring. The spindle round which the thread passes is geared on to the axle carrying the indicating needle which travels over the face of the dial; so that the elongation due to the varying temperature brought about by the different E.M.F.'s can be readily indicated.

FIG. 101.



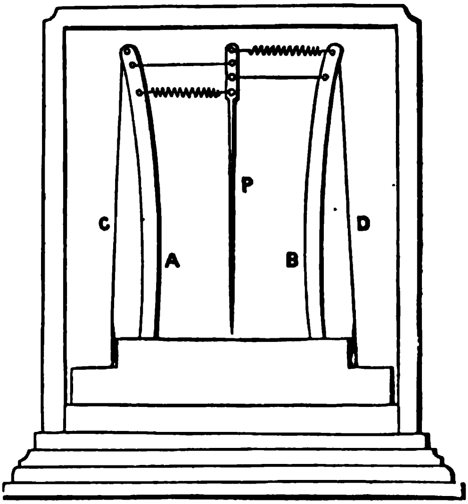
A fine platinum-silver wire fuse is introduced between the brass strips on the left of the figure. The long tube which carries the wire is in two parts, one of brass and the other of iron, so as to allow it to expand equally with the wire under atmospheric changes.

The instruments are usually made to register up to 120 volts, but the values of the readings can very easily be increased by inserting in the circuit, in series, resistance coils of various multiplying powers. Thus, if a coil equal in resistance to the wire in the voltmeter were introduced, it would exactly halve the potential difference of the current at the terminals of the voltmeter due to any particular E.M.F. Manifestly, such a coil would have a multiplying power of two, while a coil of three times the resistance would reduce the proportion of potential difference absorbed by the voltmeter to one-fourth, and therefore have a multiplying power of four. These resistance coils, however, must not be of the ordinary type. The wire should be of platinum-silver, of the same gauge as in the voltmeter, and in order to produce exactly equal facilities for radiation it should be bare, and, for convenience, it may be stretched over a kind of rectangular framework made by attaching two rods of slate to a couple of strips of wood, notches being made in the slate to receive the wire and prevent one portion slipping into contact with another. The wire and framework are enclosed by pieces of thin sheet iron.

The ordinary Cardew voltmeter, although the best and most useful instrument for the measurement of high voltages, is not available for the estimation of low potential differences, owing to the exceedingly small elongation due to the slight rise in temperature, and the consequent vagueness of the reading which would result therefrom.

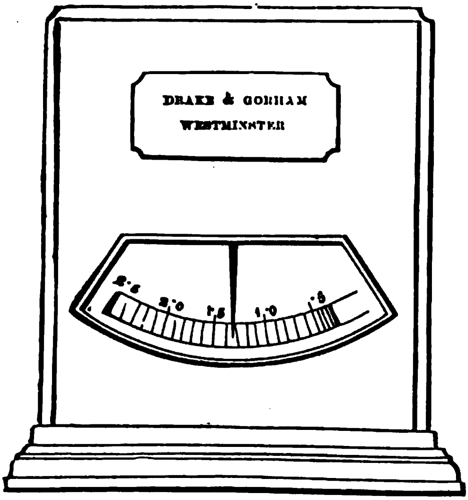
Recognising the necessity for the production of an instrument capable of measuring low E.M.F.'s—more particularly for testing the voltage of secondary cells—Major Cardew has just designed one, the working parts being shown in fig. 102. The range is from 0·5 to 2·5 volts, the scale, as shown in fig. 103, being divided into tenths of a volt.

FIG. 102.



Two pieces of platinum-silver wire, C and D (fig. 102), are kept taut by means of the upright bows, A B. The indicating needle P is supported and held in position by two horizontal pieces of wire and a couple of spiral springs. The lower ends of the wires C D are connected to terminals on the case of the instrument, so that when a current passes through the instrument it travels up one wire and across, by way of the thicker part of the needle, to the other wire. This current raises the temperature of the wires C and D, which, by their consequent ex tension, allow the upper ends of the bows to approach each other. This motion is transmitted by means of the stiff horizontal wires to the needle, which therefore travels over the scale from right to left. In the figures the needle is shown over the centre of the scale as if deflected by the application of an E.M.F. of 1·33 volts. It will be observed that there is absolutely no friction a most important feature, which, as a matter of fact, renders the instrument a possibility. It is also an inexpensive piece of apparatus.

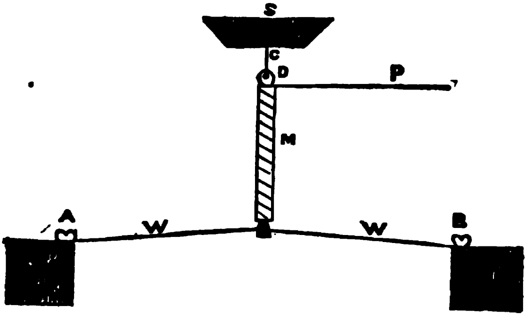
FIG. 103.



Professors Ayrton and Perry have introduced another, but somewhat more complicated, modification of the Cardew voltmeter, which is capable of accurately measuring low potential differences, and indicating small fractions of a volt. The principle upon which this apparatus is constructed will be easily understood by a reference to the diagram, fig. 104. W W is a short piece of platinum-silver wire, 0·0014 inch in diameter. The ends of this wire are held rigidly by the terminal screws A and B. The centre of the wire rests in a stirrup supported by the magnifying spring M, which is similar to that illustrated in fig. 61. The upper end of the spring carries a pointer P, and is kept in position by a piece of fine wire, C D, fixed, at its upper extremity, to the support S. On a comparatively feeble current—that is to say, a current caused by a small difference of potential—passing through the wire W, it is elongated and the sag is increased. The tension on the spring is thereby reduced, and, the lower end being fixed, the upper end revolves and carries the pointer with it. The pointer moves over a dial, and indicates directly the amount of coiling to which the spring is subjected by the sag on the wire. So sensitive is this arrangement that when the initial sag on the wire is comparatively small—that is to say, when the wire is stretched almost in a straight line between the terminals sufficient change in the sag results from the application of a potential difference of eight or ten volts at the extremities of a wire eight inches long, to produce, when magnified by the spring, a complete rotation of the pointer.

If, in a voltmeter of this kind, the wire is further shortened, the instrument will indicate a still lower potential difference, because the shortening decreases the resistance, and so augments the current resulting from a given potential difference, and also because, the mass of the wire being reduced, its temperature rises higher with a given quantity of heat. But the wire cannot be shortened indefinitely, as it is so fine that the temperature beyond which it is unsafe to work is quickly reached. It is, however, possible to obtain the first-mentioned effect without the second. For instance, in the case of what may be called the bicycle-wheel form of instrument (fig. 105), the whole of the wires can be joined in series, or grouped variously in parallel. In the latter case, the resistance being much decreased, the stronger current develops a greater amount of heat in the spokes, thus affording a means by which an instrument may be used for much lower potential differences than it can be with the spokes in series. The mass

FIG. 104.



of metal affected by the heat is, however, the same in either case.

The design of this form of the instrument is ingenious. Round a ring of metal a number of non-conducting studs, A B C, &c., are fixed. There is also a small non-conducting central piece, P, to which a magnifying spring is attached, at right angles to the plane of the ring. One end of the wire is attached to the stud E, and passes to and fro between the hub or centre-piece P and the various studs, the other end being fixed to the stud F. This device has the advantage that every portion of the wire is affected by the current, so that there is no need to introduce resistance coils into the external circuit to indicate the higher voltages, all that is necessary being, as already indicated, to join the 'spokes' in series.

FIG. 105.

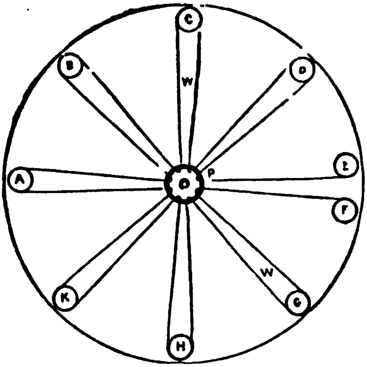
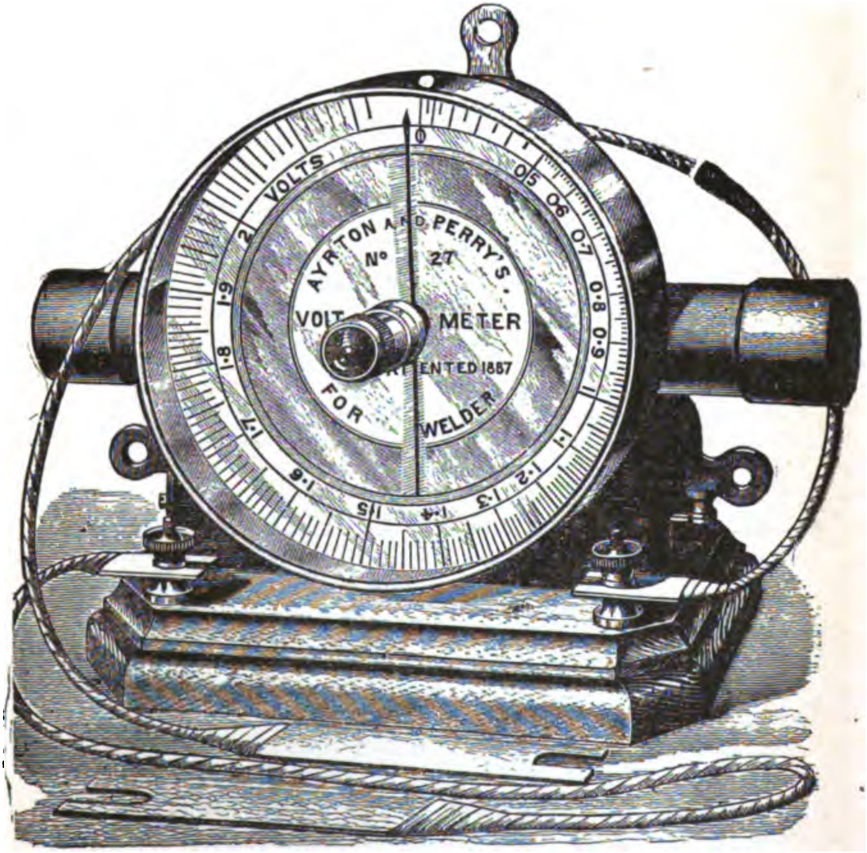


Fig. 106 is a general view of one of these hot wire voltmeters, constructed to measure the alternating potential difference at the terminals of a coil used in electrical welding, which ranges between 1 and 2 volts. The scale is 6 inches in diameter and divided into hundredths of a volt.

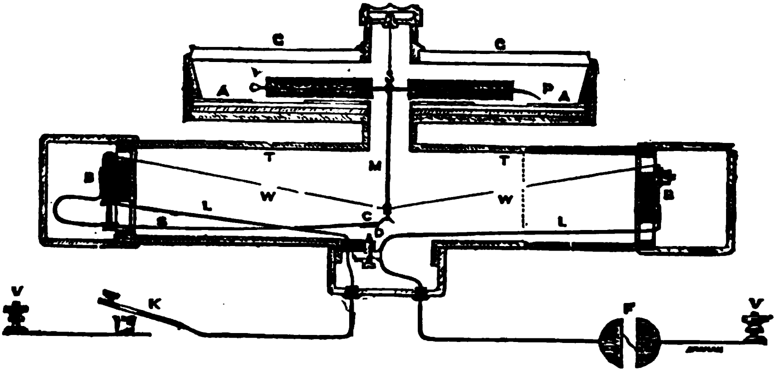
In the original instruments, the principle of which is illustrated in fig. 104, the pull of the magnifying spring M was counterbalanced by the pull of the platinum-silver wire W W attached to the terminal blocks; but in the recent form, of which fig. 107 is a horizontal section, both these pulls act, in order to economise space, in the same direction, and are counterbalanced by the flat spring S. Hence, as the wire stretches, the magnifying spring M is stretched, and the pointer P (provided with a number of fine hairs for damping without any great inertia) rotates in front of the dial. The flat spring S has therefore the effect of reducing the dimensions of the instrument, and it also allows of the adoption of a neat arrangement for a fuse, to protect the wire from an overstrong current. In the ordinary Cardew voltmeter, with a wire two yards in length, the introduction of a short fuse which will melt with a current just too small to damage the instrument does not seriously increase the resistance or diminish the sensibility; but in this modification, which sometimes contains only 8 inches of wire, the introduction of such a fuse would considerably diminish the sensibility, and it is practically impossible to diminish the length of the

FIG. 106.



fuse in proportion to the length of the working wire, in consequence of the fact that the metallic blocks to which the fuse-wire would have to be attached would conduct the heat away so rapidly as to prevent an extremely short piece of wire from melting. To overcome this difficulty a fuse, F, is employed, of such a diameter that it would require a far larger current to melt it than would suffice to damage the instrument. A small platinum-tipped screw, D, electrically connected with the wire L, passes through a small insulating block, so that when the wire W W stretches by any pre-arranged percentage beyond the amount it stretches for the maximum safe potential difference, the platinum contact C on the flat spring S makes contact with the screw D, and the working wire is consequently short-circuited. The circuit is then temporarily completed through the screw D, a portion of the wire L, and the fuse F, when the current proportionally increases and the fuse is melted without any risk of damage to the instrument. It follows that by this arrangement a thick fuse-wire can be employed, offering but a small resistance compared with that of the working wire, while the sudden application of a potential difference five or six times as great as the maximum potential difference the voltmeter is intended to measure, melts the fuse readily. The fuse F, key K, and terminals V V are shown, for simplicity sake, detached from the instrument, their actual position being, of course, on the base.

FIG. 107.



It may be added that the sensitiveness of the instrument depends in a great measure upon the initial sag given to the wire, and great care is therefore exercised in this part of the adjustment.

We come now to a consideration of the means adopted to convert the instruments which we described in Chapter IV. as available for the measurement of current strength, and which are called ammeters, so that they can be employed as voltmeters.

An ammeter measures directly the strength of the current flowing through its coils, and this current is proportional to the difference of potential at the terminals of the instrument. It might, therefore, at first sight appear that any ammeter could be used to measure the potential difference between any two points by simply joining it up to them, observing the strength of the current flowing, and from that inferring the difference of potential which maintains it. But the very act of connecting two points in a circuit by the low resistance ammeter would alter the distribution of the potential difference considerably, because an instrument to measure the potential difference absorbed between any two points in any portion of a circuit is usually applied as a shunt.

Consequently, although the ammeter so placed would correctly indicate the potential difference between the two points *after* they were so joined, it would give no information as to their condition before. For instance, if a piece of German-silver wire, having a resistance of 5 ohms, forms part of a circuit through which a current of 4 amperes is flowing, we know that the difference of potential between its terminals is 4 × 5 = 20 volts, since E = C R.

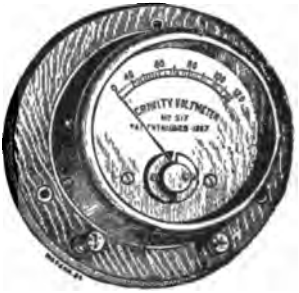
If we proceed to measure these volts, by connecting an ammeter having a fraction of an ohm resistance to the ends of the wire, we shall get much less than 20 volts, for the resistance, and therefore the fall of potential, in that portion of the circuit will have been considerably lowered. Although the total current in the main circuit will be increased by this lowering of the total resistance, the ammeter resistance is so low that it shunts the greater part of the current from the German-silver wire; and supposing that, in consequence, only half an ampere flows through that wire, the potential difference at its ends will be C × R = ·5 × 5 = 2·5 volts only, instead of 20.

In order that the introduction of the instrument should make absolutely no alteration, no current at all should flow through it; and although there are instruments which satisfy this condition, the majority are only suitable for use in the laboratory. If, however, we take any ordinary ammeter and wind it with a large number of turns of fine wire, so that it has a very high resistance, it can be used as a voltmeter; for its resistance will be too great, and the current which passes through it will be too small, to make any sensible alteration in the potential difference which it is measuring; while, on the other hand, the large number of turns of wire will allow the feeble current so flowing to produce a sufficiently strong magnetic field to actuate the movable part of the apparatus. For instance, one of the ammeters, described in Chapter IV., when wound with fine wire to a resistance of about 2,000 ohms, will serve to measure potential differences of from 60 to 120 volts. Of course, it can and must be 'calibrated' for reading in volts, in the same way that the ammeter was calibrated for reading in amperes.

One important source of error must, however, be guarded against; it is due to the fact that a current, in passing through the coils of a voltmeter, heats the wire and increases its resistance, and consequently a given difference of potential will send a weaker current through the coils after they are heated than before. The instrument will therefore indicate a lower difference of potential than that which actually exists, in consequence of the fact that it measures the potential difference by the strength of the current set up by that difference. For this reason great care must be exercised to prevent the coils of a voltmeter being heated to any appreciable extent by the current, and in order to secure this condition a key should always be supplied with such an instrument. The reading can then be taken immediately the circuit through the coils is completed by the depression of the key, and before the resistance rises. In the case of an ammeter the resistance of the coils is so very low that but little heat is generated therein, and, the size of the wire being comparatively great, the temperature, and therefore the resistance, varies but slightly Further, as an ammeter is not used as a shunt, but is placed directly in the circuit, it is virtually free from this 'heating error,' because, under all circumstances, the strength of the current flowing through it and measured by it is the same as that in the rest of the circuit.

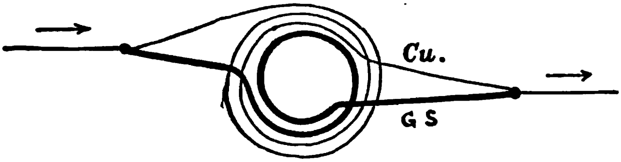
The Shuckert, the Steelyard, and the Eccentric-iron-disc ammeters, and many others of a similar character which we have not described, can be converted into voltmeters by the simple substitution of a long-wire coil of high resistance for the short-wire coil of low resistance, and this, apart from the calibration, being the only essential difference between these types of instruments, there is no need to further enlarge upon them. An exception may perhaps be made in the case of Evershed's Gravity voltmeter, a general view of which is given in fig. 108. Its moving parts are exactly similar to those of the Gravity ammeter shown in fig. 67, but, of course, thin wire, offering high resistance, is employed. Only a portion of this wire forms the actual magnetising coil, this being of copper, while the remainder, which is of German silver, is wound round a large metallic cylinder inside the casing. In an instrument indicating up to 110 volts the total resistance would be rather over 2,000 ohms, that of the actual magnetising coil being about 200 ohms, so that, with the maximum potential difference, the power absorbed is only 6 watts; and, as the temperature coefficient of German silver is low, as also the disposition of the wire gives fairly good facilities for radiation, its temperature does not rise appreciably. Consequently, the instrument may be left continually on the circuit without causing any error worth noticing under ordinary working conditions.

FIG. 108.



For cases where it is imperative that the indications should be entirely free from heating error, Mr. Evershed has suggested a very ingenious method of compensating which may be applied to this or any similar voltmeter. It is based upon the observed fact that the temperature coefficients of metals are different—that is to say, a given rise of temperature causes a greater increase per cent. in the resistance of some metals than of others, the difference in certain cases, such as copper and German silver, being considerable. The magnetising coil proper consists of German-silver wire, and a higher resistance coil of copper wire is wound round it in the reverse direction, as indicated in fig. 109, the two being connected in parallel, so that the copper coil not only forms a shunt to, but opposes the magnetic effect of the other coil, the resultant force acting on the needle being due to the excess of the magnetic effect of the German silver over that of the copper coil. The wire of the latter is made very thin, to enable the necessary resistance to be obtained while keeping the ampere turns sufficiently low, the number of ampere-turns in the German-silver coil being several times greater than in the copper. When the current or atmospheric changes cause a rise in temperature, and therefore also in resistance, the current in the German-silver coil decreases slightly, but that in the copper coil decreases in a much faster ratio, because the temperature coefficient of copper is so much greater; and if the resistances and diameters of the two wires are made such that the current in the copper coil decreases just fast enough to keep the difference between the magnetic effects of the two coils constant, the instrument will compensate itself for any variation in temperature. Unfortunately, the calculations required are somewhat difficult, and the copper wire must be extremely thin, so that this extremely ingenious method has not yet made much headway.

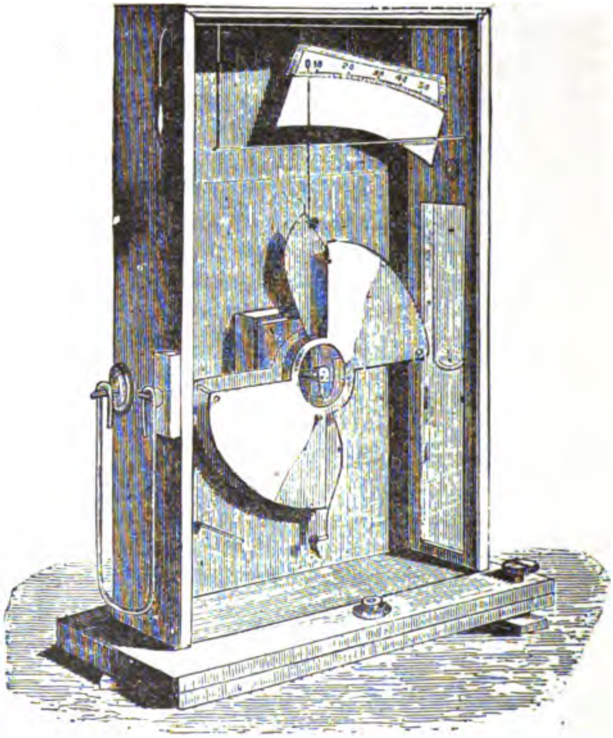
FIG. 109.



In the recent development of electric lighting the tendency is towards the use of very great differences of potential, much greater than any we have hitherto dealt with. In one case, for instance, it is proposed to work at a potential difference of 10,000 volts. This potential difference is alternating, thus excluding at once a large number of measuring instruments; and it will readily be conceived that those which we have described as capable of measuring alternating potential differences could not well be modified so as to measure up to 10,000 volts. A voltmeter has been introduced by Sir William Thomson, based upon the well-known elementary fact that two adjacent bodies at different potentials mutually attract each other. We have seen that a simple way of establishing this difference of potential is to rub two dissimilar substances, such as a piece of flannel and a piece of sealing-wax, together; they will then mutually attract each other, and the force of this attraction might serve to estimate the potential difference between them. But there is a difference of potential between the two poles of a battery; if these two poles are connected one to each of two insulated metal conductors (say brass spheres), the spheres will be at different potentials and will attract each other; the force of attraction is, however, too feeble to cause any perceptible movement, unless very delicate refinements, unsuitable for workshop use, are resorted to. But for this latter fact, such a method of measuring potential difference would be perfect in one respect, for, as the two conductors are insulated, no current whatever would flow from the battery, and we might therefore measure the potential difference without altering it during the act of measurement. The use of this 'electrostatic' method, however, becomes practicable in the case of several hundred volts, and fig. 110 shows Sir William Thomson's voltmeter, which is based upon it.

One conductor is fixed and the other movable; the fixed one consists of two butterfly-shaped sheets of brass, parallel to each other, and metallically connected, but carefully insulated from the rest of the instrument. The movable conductor is a thin aluminium strip, supported at its centre on a knife-edge, and moving freely in a vertical plane exactly midway between the two fixed brass plates. When at rest the movable plate or strip is kept in a vertical position by very small weights placed on a knife-edge at its lower extremity. If a difference of potential is established between the fixed plates and the movable strip, mutual attraction results, and the aluminium tends to set itself in a position, as far as possible, inside the fixed plates, this tendency being counteracted by the weights which it carries. The force of attraction is proportional to the square of the potential difference; the movable conductor, of course, comes to rest when the forces due to the electrostatic attraction and to gravity balance, and this position of rest is indicated by a light pointer moving over a graduated scale. This scale has 60 divisions, which represent equal differences of potential, and a large range is obtained by varying the balancing weights. When a weight of 32·5 milligrammes is used, the pointer moves through one division for a potential difference of 50 volts; with 130 milligrammes one division corresponds to 100 volts, and with 520 milligrammes to 200 volts. But with 10,000 volts or upwards there is danger of sparking between the plates in this particular instrument; it is, however, possible to increase the distance between them, and then to measure much higher by this

FIG. 110.



method. A terminal on the left-hand side of the case is connected to the fixed brass plates; while one on the right-hand side is joined to the support of the knife-edge, thus enabling connection to be made with the movable aluminium plate. A safety fuse, consisting of a piece of fine copper wire protected by a glass tube, is introduced between the fixed plates and the left-hand terminal, so that should a spark dart across between the plates, the fuse, wire will melt and, breaking the circuit, prevent the establishment of an 'arc.'

CHAPTER VII.

ELECTRO-MAGNETS—ELECTRO-MAGNETIC INDUCTION.

IT has been observed that the air space in the neighbourhood of a wire, in which the effect of a current travelling in the wire is perceptible, is called an electro-magnetic field, and that the direction in which the force in this field acts can be made evident by means of iron filings, which, if sprinkled upon a sheet of paper with the wire passing through it, arrange themselves in concentric circles along the lines of force round the wire. And further, it will be remembered that some substances offer greater facilities than others for the propagation of these lines of force, and that it is possible to alter their circular form by bringing near them some substance through which they pass with either more or less ease than through the air. The relative capability possessed by any substance for conducting these lines of force is known as its 'permeability,' and it is obviously desirable that some method of definitely comparing this property in various bodies should be adopted. The permeability of air[1] can be taken as the standard, and the permeability of all other substances measured by comparison with it.

If a piece of hard steel is placed in any magnetic field, many of the adjacent lines of force are bent out of their previous shape, and converge into the steel. More lines of force, therefore, pass through the space occupied by the steel than passed through that same space when occupied by air alone. Hence we conclude that the lines of force pass through steel more readily than through air, or the permeability of steel is greater than that of air. If, again, the steel is replaced by a piece of soft iron of similar shape and size, even more lines of force will now pass through the same space, showing that the permeability of soft iron is still greater than that of steel. In fact, the permeability of any substance might be measured by dividing the number of lines of force which pass through it, by the number which pass through the same space when the substance is removed, the strength of the magnetising field being the same in both cases. There is, however, no method available for determining the actual number of lines of force pervading any particular space or substance. The nearest approach to such a desideratum would be to measure the relative strength of any electro-magnetic field, or of any given portion of it, because, as might be supposed, the strength of the field varies directly as the number of lines of force pervading it. But here again we are beset with practical difficulties, for, except in comparatively simple cases, even this is not ascertainable directly, and can only be deduced from other effects.

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[1] The permeability of a vacuum is taken as unity; that of air is almost exactly the same, and is a more convenient standard.

It is, however, possible to compare the strength of fields by measuring the magnitude of various phenomena which can be made to take place in them; one such method is briefly described at the end of this chapter.

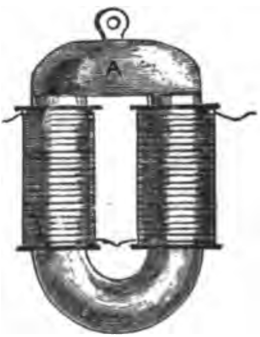
We can thus measure the strength of a field due to any magnetising force—that is, the number of lines of force passing through any given air space—and then, filling that same space with a piece of iron, measure the relative number then passing through the iron. The number of lines of force passing through an area of one square centimetre taken at right angles to them is called the amount of magnetic induction; the magnetic induction through the air space is equal to the strength of the field (since the permeability of air is 1), and the magnetic induction through the iron, divided by the strength of the magnetising field, gives the permeability of the iron.

By experimenting in this way it has been proved beyond doubt that not only do different substances possess various degrees of permeability, but also that this property may vary considerably in the same substance under certain conditions; and it is also possible to arrange the various substances in the order of their relative degrees of permeability. The most permeable material known is pure soft iron, and it is found that, generally speaking, as the hardness and impurity of the iron increase, so its permeability decreases: that of hard steel, nickel, and manganese being comparatively low. The vast majority of substances, including most of the other metals, are very nearly equal to air in this respect, while the permeability of a few metals, including bismuth and copper, is less than that of air. To take the two extreme cases, the permeability of iron has been known to reach as high as 19,000—that is to say, 19,000 times as many lines of force have been known to pass through a certain piece of iron than passed through the equivalent air space when the iron was absent, while that of bismuth has not been found to be much below 0·999968.

This property is very important in some practical operations, and (especially in the case of iron) it is useful to know the conditions under which it varies in the same material. We have already touched upon a practical application in the case of a helix or solenoid, and are now in a position to further consider the matter. We observed that the electro-magnetic effect of a helix carrying a current can be increased in two ways—either by increasing the strength of the current and so increasing the actual number of lines of force produced, whatever that number may be, or by increasing the effect of the available lines of force by making as many of them as possible pass through that space near the ends, where they will be able to act to the greatest advantage. The permeability of bismuth and copper being less than that of air, either of these substances, when placed in an electro-magnetic field, will *decrease* the number of lines of force passing through the space which it occupies; but even in the case of the most effective substance known, viz. bismuth, the difference is so very slight that it is difficult to perceive or measure it. If, however, any substance were to be discovered with a permeability very much less than that of air, one way of leading the lines of force through the desired space would be to place this substance in that part of the field from which it is wished to exclude those lines—that is to say, to make all paths but the right one, or the one desired, as difficult as possible. But the permeability even of bismuth being so little inferior to that of air, the only available method of attaining the desired end is to make the path which it is desired the lines of force should take as easy as possible. In the case of the solenoid described in Chapter IV. we wished to increase its effect by leading as many as possible of the lines of force through the ends of the coil, instead of allowing them to leak out at the sides, and for this purpose fitted it with a soft iron core, which had the desired effect. Since the permeability of different qualities of iron varies so much, too great care cannot be exercised in its selection; and, experiment having shown that soft annealed Swedish iron is superior to all other kinds, this should, when the question of expense does not forbid, be used in all cases where it is desired to concentrate the lines of force at any particular point.

It will be remembered that a helix of wire fitted with an iron core is called an electro-magnet, and electro-magnets differ in shape and arrangement according to the work they are intended to perform. Thus, if it were wished with one pole of an electro-magnet to repel a similar pole of another electro-magnet, or of a permanent steel magnet, with as much force as possible, it should be made long and straight, so that its opposite pole might be as far away as possible. It frequently happens, however, that an electro-magnet is required either to support a heavy weight or to attract another magnet or a piece of iron as powerfully as possible. It is then more advantageous to allow both poles of the electro-magnet to act together, and this can be accomplished by making it somewhat similar in shape to a horseshoe, and so bringing the poles close together, as is the case in fig. 111, winding the wire only over the 'legs' of the iron core.

FIG. 111.



In designing an electro-magnet, therefore, the object to which it is intended to apply the apparatus must be kept clearly in view, and it is necessary that the general principles underlying the science of electro-magnetic construction should be now considered, although, under the most favourable circumstances, these laws and principles are somewhat complicated and involved, and, to a great extent, indeterminate.

In the generation of an electro-magnetic field by means of a solenoid there are two prime features to be taken into consideration—viz. the strength of the current and the number of convolutions of wire constituting the coil. It can readily be seen that the electro-magnetic effect produced by a current varies directly as the strength of that current, so that to double the intensity of the field developed by any particular coil it will suffice to double the current strength. There is, therefore, no need to take into account the resistance of the wire, except in so far as it may modify the current strength, the resistance varying, of course, directly as the length, and inversely as the square of the diameter, of the wire.

As the current strength in any circuit is the same in all parts, or at all points, of that circuit, the electro-magnetic field developed by any unit length—say one inch of the wire—is exactly equal to that developed by any other portion of the circuit of equal length. It follows, therefore, that two convolutions or turns of wire close together will generate a field twice as strong as that which can be developed by either of the turns taken separately; and, speaking generally, it can be said that the field developed by a solenoid varies in strength, directly as the number of convolutions. And this will be true whatever the nature of the material forming the conductor, or whatever its resistance. Nor does the diameter of the circle described by the wire when coiled into a long helix materially affect the strength of the field developed at its centre, unless the diameter exceeds about one half the length of the coil. The dimensions of the iron forming the core have also to be taken into account, but that topic will be considered presently.

Placing these two factors together, then, the field developed by an electro-magnet can be said to vary directly as the current strength, and directly as the number of convolutions of wire, or

$$M : Cn,$$

where M is the strength of the field, C the strength of the current, and n the number of turns.

Since C is measured in amperes, this simple formula is frequently expressed by saying that the field varies as, or is equal to, the 'ampere-turns.' As the number of lines of force is proportional to the length of the wire and the current flowing through it, it would be more correct to speak of the magnetic effect as being proportional to the ampere-feet or ampere-yards; but as the term ampere-turns is generally adopted, we also make use of it.

We stated just now that the diameter of the coil was, with a certain reservation, immaterial; but it must be remembered that, supposing the number of cells in the battery to be a fixed quantity, any increase or decrease in the diameter of the coil must proportionally increase or decrease the length of the wire and its resistance, and cause thereby a decrease or increase in the current strength, unless this variation in the length of wire is accompanied by a corresponding variation in its cross-section, so as to keep the resistance constant. The all-important Ohm's law must always be kept well in view in making any changes of this sort, or serious difficulties will arise. Let us suppose that a wire offering 5 ohms resistance is coiled into a solenoid composed of, say, 10 turns, and forming one single layer, and that a current from 5 cells of 2 volts electro-motive force and 1 ohm resistance per cell passes through the coil. The current strength, supposing the connecting wires to be short and thick, and to have therefore no appreciable resistance, will be

$$c = \frac{10}{5+5} = 1 \text{ ampere,}$$

and the field will be proportional to

$$c \times n = 1 \times 10 = 10.$$

If, now, to produce an increased field, another similar layer of wire is wound over the first, the number of turns will be doubled, but the resistance of the coil will be more than doubled, for the diameter of the outer layer will be greater than that of the inner. Supposing, however, the difference in diameter to be so small as to make no material difference in the length of the wire, the current strength will be

$$\frac{10}{10+5} = {\cdot}6\dot{6},$$

and the electro-magnetic field

$$0{\cdot}0\dot{6} \times 20 = 13{\cdot}2.$$

Similarly, with a third layer, the current becomes

$$\frac{10}{15+5} = {\cdot}5,$$

and the field

$$0{\cdot}5 \times 30 = 15{\cdot}0.$$

The multiplication of the layers, therefore, does not proportionally increase the strength of the field. On the other hand, the consumption of materials necessary to the generation of the current is reduced, and the economy of the system proportionally increased. If, therefore, a coil of 99 layers were employed, and supposing for the moment all the turns to be of uniform length and resistance, the arrangement would be very economical, for the current would be only

$$\frac{10}{495+5} = {\cdot}02,$$

while the field would be

$$0{\cdot}02 \times 990 = 19{\cdot}8.$$

But, of course, the length of wire composing the ninety-ninth layer would be considerably greater than that forming the first. Now, the circumference of a circle varies directly as its diameter, and is equal to $2\pi r$, where π is the ratio between the circumference of a circle and its diameter, or $3{\cdot}1416$, and r is the radius of the circle. If, therefore, the diameter of the outside layer is actually twice that of the inside, the length of the wire in each of the larger turns, and consequently in the whole layer, will be exactly doubled, and its resistance doubled also; and the intermediate layers will vary proportionally. But the actual resistance of the whole coil can be easily calculated, for if the radius of the inside layer is half an inch and of the outside layer one inch, the mean or average radius will be three-quarters of an inch—that is to say, the length of wire in the fiftieth layer will be half as long again as that in the first. Its resistance will therefore be 7·5 ohms. Similarly, the resistance of the first and last layers together will be 15 ohms, or an average of 7·5 ohms per layer, and this will be true of every similarly situated pair of layers, so that the total resistance of a number of layers is equal to the resistance of the middle or average layer multiplied by the number of layers. In the coil under consideration the resistance will be

$$R = 7{\cdot}5 \times 99 = 742{\cdot}5.$$

and the current strength

$$\frac{10}{742\cdot 5+5} = \cdot 0133,$$

and the electro-magnetic field

$$0\cdot 0133 \times 990 = 13\cdot 167.$$

If, now, we suppose the number of layers to be again doubled, and the mean radius increased thereby to 1 inch, the mean or average resistance will be 10 ohms per layer, and the total resistance of the 198 layers 1,980 ohms. The current then becomes

$$\frac{10}{1980+5} = \cdot 005,$$

and the electro-magnetic field becomes

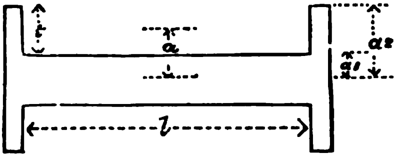
$$0\cdot 005 \times 1980 = 9\cdot 9.$$

The addition of layers of wire after a certain point has been reached has the result, therefore, of so increasing the proportional resistance as to reduce the effect which can be developed by any given battery, and this limit of usefulness or efficiency is reached when the maximum radius is twice that of the bottom or first layer.

When the field due to a certain coil, with inside and outside layers having resistances of 1 : 2, is insufficient for a given purpose, it may become advantageous to re-wind the bobbin with wire of a smaller gauge, so as to get a greater number of turns into the same compass. A reference to the diagram, fig. 112, will simplify the small difficulties involved in a consideration of this matter. Let us suppose the figure to represent a wooden or ebonite bobbin, and that the length, l, of the space occupied by the coil or the distance between the 'cheeks' of the bobbin, is 3 inches, while the radius, a_1, of the bottom layer to be wound is a quarter of an inch, and the extreme radius, a_2, of the coil three-quarters of an inch. The mean radius a will be half an inch, or

$$a = \frac{a_1+a_2}{2} = \cdot 5.$$

FIG. 112.



The total thickness, t, of the coil or of the layers will also be half an inch, or

$$t = a_2 - a_1 = \cdot 5.$$

As we have already seen, the length of one turn of wire of radius a_1 will be $2 \pi a_1$, and, it there are n turns in that layer, the length of wire composed in it will be $2 \pi a_1 \times n$. Supposing there to be m layers in the coil, having the mean radius a, the total length L will be

$$L = 2 \pi a \times n \times m \quad . \quad . \quad . \quad . \quad . \quad . \quad (1).$$

Now, as, in winding a number of layers of wire in a coil, each turn must somewhere or other *cross* the subjacent turn, it follows that the turns of any one layer cannot be placed evenly in the grooves or recesses between the turns of the layer immediately underneath it ; or, in other words, if we assume the wire, with its insulating covering, to have a diameter, d, the section of the space occupied or appropriated by that wire will really be a square whose side is equal to d. Consequently, in one layer the number of turns n will be

$$n = \frac{l}{d},$$

and the number of layers, m, will be

$$m = \frac{t}{d}.$$

Substituting these values for m and n in (1) we get

$$L = 2 \pi a \times \frac{l}{d} \times \frac{t}{d} = \frac{2 \pi a \times l \times t}{d^2} \quad . \quad . \quad . \quad . \quad (2).$$

For example, let the diameter of the wire, with its insulating coating, be 50 mils (the mil is the thousandth part of an inch), then the length of this wire that would be required to fill the bobbin illustrated in fig. 112 would be

$$L = \frac{2(3 \cdot 1416) \times 0 \cdot 5 \times 3 \times 0 \cdot 5}{(0 \cdot 05)^2} = 1885 \text{ inches} = 52\tfrac{1}{3} \text{ yards.}$$

We are thus able to calculate not only the length of wire required to fill any bobbin, but also its resistance, the resistance per unit of length being ascertainable from tables. Moreover, the total number of turns of wire can be easily calculated, for, m being the number of layers, and n the number of turns in each layer the product $m\,n$ will give the total required, but

$$m = \frac{t}{d}, \text{ and } n = \frac{l}{d};$$

$$\therefore m\,n = \frac{t\,l}{d^2},$$

$$\text{or } m\,n = \frac{0{\cdot}5 \times 3}{(0{\cdot}05)^2} = 600 \text{ turns.}$$

If, for the sake of simplicity, we suppose the wire employed to offer a resistance of 0·1 ohm per yard, the current, with the same battery as that previously used, will be

$$c = \frac{10}{5{\cdot}23 + 5} = 0{\cdot}977$$

and the field developed will be

$$0{\cdot}977 \times 600 = 586{\cdot}2.$$

As in the previous example, so in this, doubling the number of layers reduces the effective power of the coil. In working this out, it must be observed that t_1 now becomes 1 inch: therefore, also, the mean radius (a_4) of a_3 and a_1 becomes

$$\frac{a_3 + a_1}{2} = 0{\cdot}75,$$

$$\text{and } L = \frac{2\pi a_4 \times l \times t_1}{d^2} = \frac{2(3{\cdot}1416) \times 0{\cdot}75 \times 3 \times 1}{(0{\cdot}05)^2} = 5654 \text{ inches}$$

$$= 157 \text{ yards};$$

$$\text{whence} \qquad c = \frac{10}{15{\cdot}7 + 5} = 0{\cdot}483,$$

and, the number of turns, $m\,n$, being 1,200, the field developed will be

$$0{\cdot}483 \times 1200 = 579{\cdot}6,$$

or somewhat less than with only 600 turns.

Let it now be supposed that a given bobbin—say of the dimensions shown in fig. 112—is to be filled with copper wire which shall offer a definite resistance, say 5 ohms. There are thus only three quantities known, viz. the dimensions of the bobbin, the resistance which the coil is to offer, and the specific resistance of the copper; while the length of the wire and its diameter are unknown and require to be ascertained. The space in which the wire is to be wound can be calculated from the given dimensions, for, V being this space or volume,

$$V = \pi\, l\,(a_2^2 - a_1^2), \quad \ldots \ldots \quad (1).$$

$$\text{or } V = 3{\cdot}1416 \times 3({\cdot}75^2 - {\cdot}25^2)$$

$$= 4{\cdot}7124 \text{ cubic inches.}$$

But supposing, as will be actually the case, that the wire, whose diameter is d, occupies the same space that it would take were it to be square instead of round, then, manifestly,

$$V = L \times d^2. \quad \ldots \ldots \quad (2)$$

As, also, the total resistance of the wire varies directly as its length, directly as its specific resistance s (which, in this case, we take as the resistance per cubic inch), and inversely as the area or cross-section of the wire,

$$R = \frac{L \times s}{area}.$$

But the area of the insulated wire is equal to $\pi\, r^2$, or $\pi\left(\frac{d}{2}\right)^2$, that is, $\pi\frac{d^2}{4}$.

Therefore
$$R = \frac{L \times s}{\pi\frac{d^2}{4}},$$

that is,
$$R\,\pi\frac{d^2}{4} = L\,s,$$

or
$$R\,\pi\,d^2 = 4\,L\,s,$$

and
$$d^2 = \frac{4\,L\,s}{R\,\pi} \quad \ldots \ldots \quad (3)$$

But from (2) it will also be seen that

$$d^2 = \frac{V}{L} \quad \ldots \ldots \quad (4).$$

Consequently
$$\frac{4\,L\,s}{R\,\pi} = \frac{V}{L} \quad \ldots \ldots \quad (5).$$

and $$4\,L^2 s = \pi\, R\, V.$$

Therefore $$L^2 = \frac{\pi\, R\, V}{4\, s},$$

and, finally, $$L = \sqrt{\frac{\pi\, R\, V}{4\, s}} \quad . \quad . \quad . \quad . \quad . \quad (6).$$

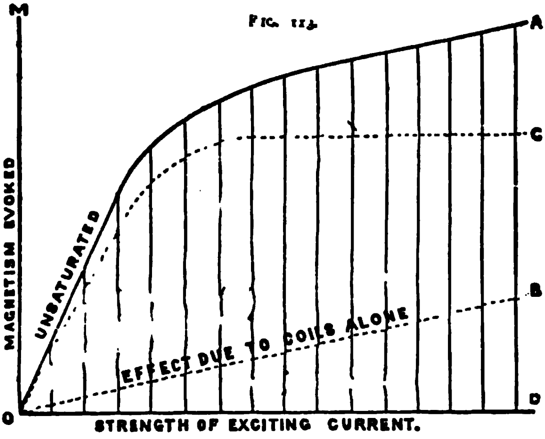
By inserting the numerical values on the right-hand side of this equation, the length L, having the required resistance, can therefore be found, after which we can, by equation (4), determine also the gauge of the wire. It must, however, be noted that, for simplicity, d is taken as the diameter of the bare wire in equation (2), thus rendering the result only approximate; but when the thickness of the wire is great as compared with that of the insulation, the formulæ approach very closely to the truth.

It is frequently useful to know the exact length of any particular wire which can be wound on any particular bobbin, and, knowing V and d, this can be easily ascertained, for, if d_1 represents the outer diameter of the wire and its covering, V the volume of the wire-space, and L the required length, then

$$L = \frac{V}{{d_1}^2}$$

So far, very little has been said concerning the dimensions and nature of the core, beyond the fact that it should have the highest possible degree of permeability, and be constructed, therefore, of the best annealed iron, and that there is a limit to the number of lines of force which can easily be passed through an iron core. These considerations render necessary the employment of a relatively massive core, having, for the best electro-magnetic effect, a diameter equal, at least, to the thickness of the coil with which it is to be surrounded—that is to say, its diameter should correspond to the thickness t in the ideal coil illustrated in fig. 112. It is here that the question of relative permeability has to be taken into consideration, for it has been experimentally demonstrated that there is a limit to the number of lines of force that can be transmitted by a given mass of iron, and that this limit is soon exceeded when the diameter of the core of an electro-magnet is small as compared with that of the coil which surrounds it. The permeability of a rod of iron decreases as the lines of force passing through it increase, so that, beyond a certain point, a considerable increase in the strength of the current makes but little difference in the electro-magnetic force developed at the poles. When it thus becomes very difficult to urge additional lines of force through a piece of iron, it is said to be magnetically 'saturated,' but no definite point has yet been reached at which it can be said to be absolutely impossible to increase the number. Many definitions of the so-called 'saturation' point have been given, but they are generally based upon a misconception of the question, and some of them are altogether misleading. There is abundant evidence of this, if evidence were wanting, in the fact that no two authorities have yet been able to agree upon the saturation point even of iron, to say nothing of steel, and the majority are satisfied by referring to historic experiments, which, however, were made at a time when iron, such as is now in every-day use, was unobtainable. As a matter of fact, if 100 different samples of iron were taken and experimented upon, it is more than likely that as many different results would be arrived at, for the saturation point depends solely upon the permeability, and the permeability of any particular piece of metal depends greatly upon its molecular structure. Now, the permeability of air is constant, although it is low as compared with a piece of 'unmagnetised' iron. In other words, there is no magnetic saturation point for air, so that, through an air-space which already has a great number of lines of force traversing it, it is as easy to urge more, as it would be if there were none already in existence. It follows, therefore, that at a certain stage of the magnetising force developed in or by a coil of wire, the permeability of air equals, and beyond that stage exceeds, the permeability of iron. A consideration of these points demonstrates that the core of an electro-magnet should be sufficiently massive to prevent the saturation point being reached, or, at any rate, passed, when the maximum current which it is intended that the coil shall carry is passing. This will be evident by a reference to fig. 113, in which the relative strengths of the magnetic fields under different conditions are shown by the 'curves' plotted out on a sheet of 'squared' paper. This squared paper is exceedingly useful. It is usually ruled with a number of equidistant horizontal and vertical lines, the former being, however, omitted in the present instance. Let it be supposed that the line O D is divided into a number of equal parts, corresponding to the various current strengths, so that from O to the tenth division would represent five times the current strength that would be indicated by two such divisions. Let us also suppose that O M is divided equally, and that the divisions correspond to the various magnetic effects produced by an electro-magnet upon a compass needle balanced at some distance from it, and in the same horizontal plane as the axis of the coil. Let us now suppose currents of various strengths, indicated by the distances along O D, to be sent through the coil, the effect which the coil with its core exerts upon the compass needle can be marked off from the line O M upon the various ordinates projected from O D. The thick upper curve O A drawn through the intersecting points shows graphically, by its distance from O D, the deflecting effect produced upon the needle by the various currents corresponding to the distances along O D. Let it be further supposed that, without in any way altering the position of the needle or of the coil, the core is withdrawn and the various currents again sent through the coil. Then the various magnetic effects of the coil upon the needle are clearly indicated by the 'curve' O B, which, in this case, is a straight line, and which demonstrates, therefore, that the field produced by the coil is pro-

FIG. 113.



portional to the current flowing through it. The third curve O C is particularly interesting. Suppose the magnetic effect due to the coil alone, and represented by the distance D B, to be deducted from the joint effect produced with the same current by the core and coil combined, and represented by the distance D A, then the remainder D C will represent the effect produced by the core alone. And if this subtracting process is carried out along each of the ordinates, the curve O C, known as the curve of magnetisation, will be produced. Now, it will be observed that, after a certain point has been reached, this curve becomes a nearly horizontal straight line, indicating that the saturation point of the iron has been reached, and that any further increase in the current strength does not add appreciably to the magnetisation of the core, the increase in the strength of the field developed being that due to the coil itself. The two curves O C, O B, would, if the experiments were carried far enough, intersect, at a point where the permeability of the air equals that of the saturated iron.

Pure soft iron has another property which recommends its adoption for the cores of electro-magnets, and that is its low 'retentivity,' for, as a rule, electro-magnets are required to develop as strong a field as possible at some particular point directly the current commences to flow, and to lose or be deprived of all traces of magnetisation on the cessation of the current. Steel, as we have already seen, always retains a large proportion of the magnetic state impressed upon it by the projection of an electro-magnetic field through it, or, in ordinary language, it retains the magnetism imparted to it. Hard and impure iron have similar properties, inferior only to steel itself. There is no doubt that these properties of permeability and retentivity are very largely governed by the molecular structure of the iron or steel, and by the greater or less rigidity obtaining among the particles of the metal. In fact, the two properties go together; for all qualities of iron or steel through which it is difficult to urge the lines of force, or to magnetise, are found to be correspondingly obdurate when it is sought to demagnetise them, or deprive them of magnetisation. There is, therefore, a double gain in employing pure soft iron, for not only is its permeability greater, but its retentivity is also less than that of impure or hard iron.

On the other hand, in selecting a material for permanent magnets, the principal thing to be considered is the retentivity, which, of course, should be as high as possible. No substance has yet been found which is, in this respect, superior to good hard steel. Some specimens of steel have been made so hard that efforts to magnetise them have proved futile. One of the most remarkable features to be observed in this matter is the extraordinary effect produced by the admixture of a small—one might almost say a minute—proportion of other, or foreign, substances with the iron. Just as a fractional proportion of iron or other metal added to copper causes a large increase in its electrical resistance, so the addition of carbon, tungsten, phosphorus, sulphur, arsenic, &c., to iron, reduces its permeability and also increases its retentivity. This reduced permeability corresponds, in many respects, to increased electrical resistance in a conductor, and is, in fact, sometimes referred to as increased magnetic resistance. In the case of ordinary steel the retentivity is evidently due, in a great measure, to the presence of carbon, and, with a bar of good magnet-steel, the permeability is so feeble, and the retentivity so great, that it is impossible, by electro-magnetic induction, to upset the molecular arrangement in the interior of the bar, so that the magnetisation is in reality only skin-deep. This can be easily proved by magnetising a small. piece of very hard steel and then immersing it in dilute sulphuric or hydrochloric acid. In a few moments the surface of the metal will have been dissolved, and on withdrawing it from the liquid all trace of magnetisation will have disappeared. Consequently, it is preferable, in making a large permanent magnet, to build up a number of thin strips of steel cut to size and then magnetised separately. On fastening them together, the built-up, or 'laminated,' magnet will be found capable of producing a far stronger field than can be obtained with any solid magnet of similar dimensions. It should, however, be added that in building up a compound magnet, or 'magnetic battery,' there is no advantage in employing *brass* screws or bolts to fasten the individual magnets together as is usually done. In fact, this plan cannot but disperse the lines of force passing through the magnets, and therefore weaken, more or less, the polar strength. Iron screws or bolts are mechanically and magnetically preferable.

It is interesting to notice that specimens of steel have been made, containing 12 per cent. of manganese, which it has been found practically impossible to magnetise even under the influence of a very powerful field. Probably, the magnetic reluctance, molecular rigidity, magnetic inertia, or whatever else we may choose to call that property of steel which our forefathers knew as coercive force, is so great, that to overcome it is impossible. Similar results follow when the proportion of carbon, phosphorus, sulphur, &c., mixed with the iron exceeds a certain small limit, while the admixture of even the smallest percentage of antimony suffices, it is alleged, to destroy all trace of magnetic properties. There should certainly be a large field of practical utility open to the economical manufacture of unmagnetisable iron. For example, the bed-plates of dynamos are sometimes—and used to be even more extensively than now—separated from the field-magnets by huge slabs of zinc, because, otherwise, they would form what may be called a magnetic short-circuit between the poles of the field-magnets. Zinc is mechanically much weaker than iron, and this, added to its very much higher price, renders its use highly objectionable. To avoid the difficulty, dynamos are rarely designed now with their pole pieces downwards, but are turned about so that the bed-plate is connected to the yokes or magnetically neutral portions of the field-magnets. Under such circumstances only a very few of the lines are wasted by passing through the bed-plate. Reverting to the question of magnetic inertia, it may be mentioned that any cause which may operate to set up molecular vibrations in a piece of iron or steel facilitates either magnetisation or demagnetisation — that is to say, if the metal is placed in a magnetic field and then vibrations set up in it, it will be more readily and more powerfully magnetised than would be the case were the vibrations not set up, and, conversely, a magnet loses its magnetisation by being set in vibration, due to the fact that facilities are thereby afforded for the individual particles, which are themselves magnets, to partially rotate and form little closed magnetic circuits in the mass of the metal. These vibrations can be caused by heating, hammering, twisting, or any other similar violent treatment. Hence, steel magnets should always be placed down gently, and never dropped or thrown down, otherwise the magnetisation will be more or less destroyed.

A magnet raised to a red-heat loses its magnetisation entirely, and this can easily be demonstrated by heating a magnetised sewing needle in a gas flame.

By adopting the precautions referred to, magnets can be made capable of sustaining considerably more than thirty times their own weight, but a description of the method practically adopted for the manufacture of permanent steel magnets capable for some years of supporting about twenty-five to twenty-eight times their own weight may prove serviceable. In this case, the best tungsten steel is employed. It is heated gently to a dull red heat and hammered into the required shape, care being taken not to raise the temperature too high, or the tungsten will be volatilised. A small magnet may therefore require to be placed in the fire several times before the necessary shape has been obtained. This process being completed, the steel is then hardened by being first placed in a close fire out of contact with air, so as to ensure uniform heating and to prevent the formation of a hard scale of iron oxide. It is then dipped into a water bath. This latter process must be carefully attended to, or the metal will be twisted or otherwise distorted. It should be held vertically, and, if of the horse-shoe pattern, its extremities should be dipped in first, the metal being steadily lowered into the water. The next process is that of polishing, after which it is passed a few times over the poles of a large and powerful permanent magnet, the steel being turned over once or twice so as to magnetise both faces. Of course, a large electro-magnet, with a powerful current circulating through its coils, can be employed, but the other form is quite efficient and certainly much less troublesome.

We have not yet, however, said all that requires to be said upon the subject of electro-magnets. One important detail, so far neglected, is the length of the coil and of the core, as compared with the diameter. It has already been laid down that the maximum, or outside, diameter of the coil should not exceed three times the diameter of the core; but although it is often stated that the best result is obtained when the length of the core is six times its diameter, we have failed to discover any universal reason for such a proportion. As a matter of fact, with a bar-magnet, where we desire to employ only one pole, and wish to mask or get rid of the effect of the other, there is a decided advantage in using a core of much greater proportional length, and if we are restricted as to the quantity of wire to be employed, we can then wind fewer layers over a long piece of iron than would be wound over a shorter piece. By so doing we should reduce the distance between the iron and the wire, and therefore, with the same resistance, the number of lines of force passing through the core would be correspondingly increased. Supposing, however, the same proportion to be maintained between the respective diameters of the lengthened core and its coil, and the gauge of the wire increased so as to maintain a constant resistance and constant number of turns, the polar strength developed close to one end of the core will vary as the square of the length of the core, providing, however, that the core is not so extensively lengthened as to cause many of the lines of force to 'leak out' at the sides of the coil. This limit will, of course, vary with different qualities of iron, as the question is mainly one of relative permeability. Sometimes there is an advantage in using very short electro-magnets, as, for example, when it is desired to obtain one which shall respond promptly to variations or reversals of the magnetising current.

So far, we have only considered electro-magnets in which the wire is wound evenly throughout their length, but, for some purposes, it is preferable to vary the method of winding. If, for example, it is desired to construct a bar-magnet which shall develop a very powerful field close to its extremities, but which is not wanted to exert any force at a comparatively greater distance, then the best form to give to the piece of apparatus is that in which the wire is 'coned up' near the ends that is to say, where a large number of layers is wound over the ends, the number decreasing towards the middle, few or none being wound over the central portion of the core, although at no point should the wire, as a rule, be wound to more than three times the diameter of the core. The lines of force in such an electro-magnet will be powerfully developed near the ends, and there will be little tendency for them to leak out. On the other hand, they will make much smaller air-curves than would result from an equal length of wire wound evenly along the entire length of the core.

The horse-shoe form is only adopted when it is desired to exert the maximum attraction upon a piece of iron placed near it. If it were placed at any considerable distance compared with the distance between the magnet poles, most of the lines of force would pass across the air space from one pole to the other without entering the iron. But such a magnet obeys the same law that holds good for bar magnets so far as the relative strength of the magnet, when traversed by various currents, is concerned. That is to say, if we have an electro-magnet developing a field, at a given distance the strength of the field will vary directly as the strength of the current producing it. When, however, a piece of soft iron is placed in the field, the lines of force are diverted. and, passing through it, endow it with magnetic polarity, and the polarity developed varies directly as the number of lines passing through it, or as the strength of the current. Such a piece of iron is called an armature, but we may regard it for the time being as another magnet, and when we have two magnets mutually attracting one another, the force of attraction is proportional to the product of their magnetic strengths, or the force

$$f : m \times m_1,$$

where m is the strength of one magnet, and m_1 that of the other (or of the armature).

If, now, we suppose the strength of the current to be doubled, and consequently the magnetic field developed to be also doubled, then (assuming the iron to be far from saturated) twice the number of the lines of force will pass through the armature, the magnetisation of which will therefore also be doubled, that is

$$f_1 : 2m \times 2m_1 = 4mm_1,$$

or, doubling the current strength, quadruples the magnetic attraction. Hence this attraction at any given distance varies directly as the square of the strength of the current flowing through the coil. When, however, the iron approaches saturation, the alteration in its permeability prevents any definite law being formulated.

This law is sometimes mis-stated by saying that $m = m_1$, whence $m \times m_1 = m^2$. But this is only true when the whole of the lines of force emanating from the poles of the electro-magnet m pass through the armature, and this rarely or never happens.

To ensure that the armature shall be capable of transmitting a large percentage of the number of lines of force which pass through the core, it is evident that it must at least be equal in permeability and correspondingly massive. It should certainly be equal in section to the core.

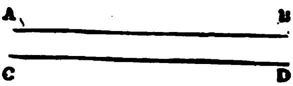
One of the best forms of the horse-shoe magnet is that illustrated in fig. 111. It will be seen that the coil is divided into two sections, placed one on each limb or leg of the core, the winding being such that, were the core straightened out and the coils pushed together so that their ends meet, they would form one continuous coil or helix. Otherwise similar instead of dissimilar poles would be developed at the extremities of the core. The iron should be the best and softest procurable, and should be bent round so that the poles are close together; a comparatively very large number of the lines of force will then pass through the space between the poles when the armature is removed. The surfaces in contact should fit as perfectly true as possible, so that there is the minimum air space between them. Sharp corners or edges should be avoided, and, since the natural shape of the lines of force is circular, the whole should approximate to the circular form, when there will be little tendency for the lines of force to 'leak out' of the iron and complete their circuit through the air space.

Horse-shoe electro-magnets are frequently constructed to sustain a weight. The sustaining power must not, however, be confounded with the strength of the field or the magnetic strength, as this power depends upon a number of secondary considerations, such as the shape and smoothness of the pole pieces or extremities of the core, the dimensions and surface of the armature, the method of applying the weight to be sustained, &c., which do not require to be taken into account when estimating the electromagnetic field itself. The weight can be suspended from a hook fixed to the middle of the armature, so that the pull upon the two poles is equal, the sustaining power being measured by the weight which can be supported by the armature without causing its separation from the magnet.

It is, however, frequently preferable, for convenience of construction, as in the case of most forms of dynamo-electric machines, as well as in telegraphic and other similar apparatus, to build up an electro-magnet in which two straight cores are yoked together by a piece of soft iron which is screwed or bolted to them. The yoke must naturally be massive, and the surfaces fit truly to avoid as far as possible the introduction of a magnetically resisting air space.

We have stated frequently—so frequently, in fact, that we almost feel it necessary to apologise for repeating the statement—that when a current of electricity is set up in a wire, an electro-magnetic field is almost immediately generated in the region surrounding that wire. But the converse of this is also true viz. that when an electro-magnetic field is suddenly set up around a wire, there is a tendency for a current to be generated in that wire *during the setting up of the field*, and if the wire forms part of a complete circuit a current will flow along it. The source of the field is immaterial: it may be a permanent magnet, a straight wire or a helix carrying a current; all that is essential being that the lines of force should be thrust across the wire, or that the wire should be moved in such a manner as to cut the lines of force *transversely*. As an instance, let A B, C D (fig. 114) be two wires running side by side for a certain distance, each forming part of a complete circuit. If a current is started in A B, lines of force will immediately start from its centre, or axis, in the form of widening circles, and, cutting the second wire, C D, set up an electro-motive force therein and, in consequence, generate an electric current. It is only, however, while the lines of force are actually cutting the second wire that the E.M.F. is developed, and as this cutting ceases immediately the current in A B arrives at its full strength, the induced current lasts but for a moment. In direction it is opposite to the current in the wire A B. While the original current is steady many of the lines of force due to it are embracing the adjacent wire C D, though, being relatively at rest, they have no effect thereon.

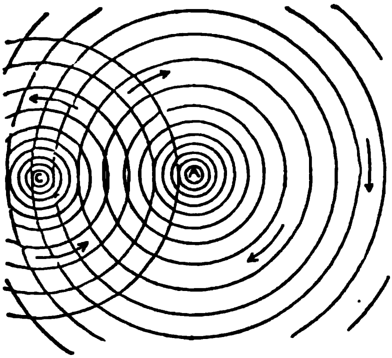
FIG. 114.



But when the current in A B is stopped, all the lines of force collapse upon it, and those which extended beyond the wire C D again cut it, and thereby induce in it another momentary current.

But, since the lines now cut the wire C D in the opposite sense (for they approach it from the opposite side), the resulting current is in the opposite direction to the previous one—that is, it is now in the same direction as the inducing current which was flowing in the wire A B. By noting the direction of the lines of force due to the inducing current, and the direction in which they must coil round the wire C D during the time they are passing it, we might predict the *direction* of the induced current in either case. It is somewhat difficult to make this clear by diagrams, but an analogy may assist us to a great extent. When any small body is dropped on the surface of still water it breaks that surface into a series of ripples which take the form of ever-widening concentric circles, as in fig. 115, where A is the point of generation. In such a manner do the lines of force spring into existence from a wire, only with far greater rapidity, and it is difficult in either case to fix a limit to their extent if the medium (the water or the ether) is not limited.

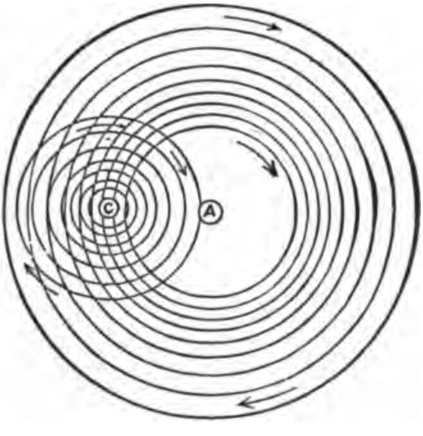
FIG. 115.



Now, if these water ripples meet any obstruction, for instance, a post at the point C, they set up around it a series of circular ripples, feebler, perhaps, but precisely similar in character to themselves. It is difficult at present to say with certainty exactly what happens in the case of the electro-magnetic lines of force, but we can safely use the analogy for the purpose of demonstrating that the direction of the lines of force round the wire in which the current is induced is opposite to their direction round the inducing wire. For, suppose, as in the case of the lines of force, the original ripples round A to have what is called a positive direction—that is to say, that they circulate in a right-handed direction after the manner of the hands of a clock, as indicated by the arrows; then, since that direction would not be altered by reflection at the obstacle C, they must go round C left-handedly or contrary clock-wise. Now, if these were electro-magnetic lines of force we know (Chapter IV.) that their direction would indicate a current flowing ***downward*** through A, and ***upward*** through C, and thus we can readily perceive how the starting of a current in one wire gives rise to an ***inverse*** one in a neighbouring wire. Further, we see that it is only while the original ripples generated from A are ***passing*** the point C that these secondary ripples can be generated or called into existence, and we may again picture to ourselves how it is that a current is induced in a wire, only during the time that the current in the neighbouring wire is attaining its full strength.

Let us now suppose it possible to cause a series of ripples to collapse upon the point A, in the same manner as we imagine lines of force to collapse upon a wire. Before arriving at A they would meet with C, and, as before, generate a series of secondary ripples, but in this case their direction round C and A would be the same, for now they approach C from the opposite side. Again assuming the ripples to have a positive direction, the arrows in fig. 116 show that their direction will be the same round each, and if A and C were wires and the circles lines of force, the current in each wire would be flowing downward through the paper. It thus becomes easy to imagine how the stoppage of a current in a wire induces in a neighbouring wire a current in the *same* direction as itself. The wire in which a current is induced is called the secondary, and the one which carries the inducing current is termed the primary wire.

FIG. 116.



Now, if in fig. 114 the wire A B, while carrying a steady current, were suddenly brought close to C D, or if C D were suddenly brought close to A B, the lines of force would cut C D in precisely the same manner as they did when a current was started in A B. The result would therefore be the same, that is, a momentary current would be developed by induction in C D, in the opposite direction to that of the current in A B. Furthermore, if the two wires were then suddenly moved asunder, C D would be cut by the retreating lines of force, just as it was cut during the stopping or the dying away of the primary current, and a direct induced current would therefore be the result.

These induced currents bear a very simple ratio to the currents producing them. The E.M.F. in the secondary wire is proportional to the number of lines of force which cut it, and also to the rate at which they cut it. Now, the number of lines of force may be increased by increasing the strength of the current in the primary wire, or by adding to the length of the wires in proximity. It is, however, more convenient to wind the longer wires in spirals or helices, when the effect will be similar to that which would result from two long straight wires. It is evident that the two wires should be as close together as possible, otherwise those lines of force very near the primary wire would not reach the secondary wire at all, and would, therefore, fail to produce any effect therein. In some cases when it is desired to obtain a powerful induced current, the primary and secondary wires are wound in the form of concentric helices, and an iron core is inserted to increase the number of lines of force which cut the secondary. Having by such means made the number of effective lines as high as possible, the only other thing to be done in order to increase the secondary E.M.F. is to make the rate at which the secondary is cut by these lines as great as possible.

Now, supposing the two wires A B, C D (fig. 114) to lie quite close together, and the current in A B to be started and to arrive at its full strength instantaneously; the rate at which its lines of force cut C D would then be a maximum, and it would not be possible to further increase the E.M.F. of the induced current, except by increasing the strength of the current in A B and so increasing the *number* of the lines of force. But in practice a current does not rise to its full strength instantaneously, nor does it stop suddenly; time is taken for the lines of force to spring into existence and to die away, and under certain conditions this time may be considerable. To understand the principal cause of this sluggishness let us refer again to fig. 115 and further study the case of the water ripples. A little thought or experiment will make it evident that the secondary ripples round C will quickly reach the point A, and if the body which caused the disturbance is still there, will set up around it ripples in the opposite sense to the original ones. Now, suppose two wooden balls, A and B, were dropped into the water at the same moment close together and equidistant from C, they would set up ripples round C, each to the same extent and in the same sense; in fact, the number round C would be doubled. But still stronger is the effect of A and B round each other, and (still assuming a positive direction just as we do for lines of force) the direction of the ripples so set up round each will be opposite to those which it generates. In the same way if a primary wire is looped into two convolutions, A and B, they will generate round an equidistant loop of the secondary just double the number of lines of force which one will; but they also react upon each other, each setting up round the other, lines of force which would generate a current tending to stop the primary one, the result being that this primary current does not rise so rapidly to its full strength. This retardation increases as we increase the number of convolutions; in fact, it varies directly as the square of the number of convolutions, because each one acts upon all the others and they in their turn act upon it. Therefore the retardation in a coil of 100 turns would be 100 times as great as in a coil of 10 turns.

In a precisely similar manner the reaction of adjacent convolutions prevents the instantaneous *stoppage* of a current; for, at the moment of disconnecting the battery or other current-generator, lines of force collapse upon each convolution, and in so doing they cut the other convolutions and generate a direct induced current which will also vary as the square of the number of turns, and tend to prolong, or retard the disappearance of, the primary current.

The electro-motive force resulting from this collapsing of the lines of force may be, and usually is, much higher than that which maintains the original current For, supposing the battery used consists of ten Daniell cells, then if the poles are connected by a short piece of wire, no spark, or, at the most, a very feeble one, is observable when the circuit is closed or opened quickly. If this same battery is made to send a current through a coil of many turns of wire, although its resistance may be high and cause the current to be comparatively weak, yet, on breaking the circuit, a spark will be observed. This is due to the fact that the lines of force fall back so quickly upon their respective convolutions in the coil, that they cut the adjacent convolutions with sufficient rapidity to generate a momentary E.M.F. high enough to produce a current sufficiently strong to volatilise a portion of the metal, and to maintain the current across the vapour-filled space for a brief interval, even after the wires are moved asunder. This effect is even more striking if in a dark room contact is broken between a wire and a mercury surface, when a little of the mercury is volatilised; and, since the effect of iron placed in the vicinity is to increase the number of lines of force which are active, the spark can be increased enormously by placing a core inside the coil.

The term 'self-induction' has been given to this action, which prevents the instantaneous rise and fall of a current, and it will be evident, from what has been said, that, in the case of a simple straight wire, this phenomenon is almost imperceptible, and that, in order to make the self-induction of any circuit a maximum, the wire should be wound into as many convolutions as possible, and be provided with plenty of iron.

In some cases it is desired to design electro-magnets which shall be affected as little as possible by brief, sudden fluctuations of the magnetising current. It is manifest that in such a case the electro-magnetic inertia—that is, the self-induction—must be made high by using a long and massive core and a great number of turns of wire; for, as we have seen, self-induction prevents a rapid rise or fall of the current, in just the same way as the 'inertia' of matter prevents any instantaneous change in its motion. If, on the other hand, an electro-magnet is required to be quick-acting, or to be very sensitive to any variation in the current, self-induction should be as low as possible, and, in order to obtain this, the coil should consist of as few turns of wire as possible, and the core should be very short, or the turns of wire should be confined to its end or ends.

The measurement of the intensity of an electro-magnetic field is, as already mentioned, a matter of great practical difficulty. However, as the movement of a wire in any magnetic field tends to set up a current in the wire, and as the field may be that of a permanent magnet, or even that of the earth, and since, also, the strength of any field is proportional to the number of its lines of force per unit area, while the current generated in a wire is also proportional to the number of lines of force cut by it, and to the rate of cutting, we may compare the strength of different fields by observing the current resulting from the cutting of them by a wire at equal speeds. It is advantageous to wind the wire into a small coil, and place it in the field with its plane perpendicular to the direction of the lines of force, and then suddenly turn it through a right angle, when its plane will be parallel to the lines of force, and none will be passing through the coil. The E.M.F. resulting will be proportional to the number of convolutions, the strength of field and the area of the coil (that is, to the number of lines of force passing through the coil), and to the speed with which the lines are removed. Special galvanometers are constructed to give the values of such sudden momentary currents, by comparing which the strengths of the various fields can be measured

CHAPTER VIII.

DYNAMO-ELECTRIC MACHINES (ALTERNATE CURRENT).

In the preceding chapters we have dealt with some of the principal laws of electric currents, and the most striking phenomena connected with them. The student will not have failed to notice two important facts: (1) That when a wire through which a current is passing is placed in a certain position in any electro-magnetic field, it has impressed upon it a definite mechanical force tending to move it into another part or out of the field; and (2) when a conductor is mechanically moved in a field transversely to the lines of force traversing that field, a certain electromotive force is determined, which sets up a current in the wire if its two ends are connected. Extensive use is made of both these effects in practice, and on a very large scale. Machines which are constructed to transform energy which exists in the form of electric currents into energy in the form of mechanical motion, and, conversely, machines which are able to transform energy in the form of mechanical motion into energy in the form of electric currents, can be included under the generic head of 'dynamo-electric machinery.'

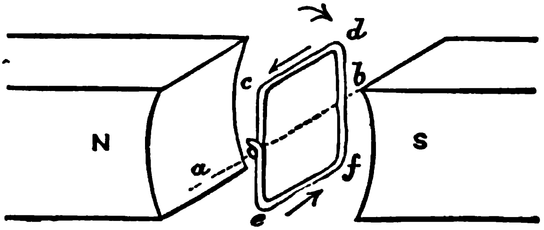
We shall first consider machines of the latter class, which are commonly known by the shorter name of 'dynamos,' deferring a consideration of the other class until an opportunity offers for dealing with such apparatus under the head of 'motors.'

In every machine for the conversion of energy, there is always a certain amount of loss attending the conversion; in other words, less energy appears in the new than existed in the original form. The more perfect the machine, the less does this loss become, so that a theoretically perfect machine would be one in which there is actually no loss at all. It is absolutely impossible to construct such a machine, but in every case the chief aim of the engineer should be to make the loss as small as possible, or to make the machine as 'efficient' as possible. The proper way of doing this is to start with the fact established in accordance with the doctrine of the 'conservation of energy,' that energy can never pass out of existence or be destroyed; that, therefore, the whole of the energy put into the machine reappears in some shape or form, although only a part appears in the exact state in which it is desired. Steps should then be taken to ascertain exactly what form the other part takes, and the designer of the machine should study how to reduce that same part, which may be called 'waste,' to a minimum. In all machines which have moving parts, a certain percentage of the energy takes the form of heat, due to friction at the bearings and other surfaces which come into contact. Every dynamo has moving parts, and is therefore subject to loss from this cause, and the well-known methods of reducing friction by good workmanship and design, and by the judicious use of oil or other lubricant, are taken advantage of to minimise the loss. But there are many other causes besides mechanical friction which operate to reduce the efficiency of a dynamo; they are mainly due to electro-magnetic phenomena, and careful study is required in discovering how to eliminate or minimise them, although in some instances the loss may be readily localised, because, like friction, these phenomena convert a certain amount of the original energy of mechanical motion into heat. One of the principal features, then, by which a dynamo is judged is its efficiency, or by the ratio of the energy re-appearing as electric currents to the total amount given mechanically to the machine.

We will start with the consideration of the simplest type of dynamo-electric machine, and, observing its weak points, endeavour to trace its development into a practical and highly efficient piece of apparatus.

Now, it is only during the time that the lines of force of a field are being cut by a conductor that an E.M.F. is induced in that conductor; therefore, in order to obtain a continuous current, or a very rapid succession of currents, it is evident that either the conductor or the field must be kept continually in motion. Let us first study the case of a fixed field and a moving wire, assuming, for the moment, that we have a strong and fairly uniform field produced by the opposite poles of two large permanent bar-magnets placed near to each other, or by any other convenient means. A uniform field has been already defined to be one in which the lines of force are straight, parallel, and equidistant. It is not easy to obtain a strong uniform field of any great extent, so that the most convenient way of continually cutting lines of force is to cause the conductor to move in a circular path, within the limits of a powerful field of comparatively small area. For instance, if the wire is bent into a single rectangular coil, as shown in fig. 117, it may be placed in the field with its plane at right angles to the direction of the lines of force, so that as many as possible of these lines are made to pass through it. If, now, this coil is turned suddenly through an angle of 90° about the axis *a b*, its plane lies parallel to the lines of force, and it is obvious that none of them now pass through the coil. In the act of turning, both the top and the bottom limbs, *c d* and *e f*, cut a certain number of lines, setting up thereby an electro-motive force in the wire; but as these two horizontal limbs of the rectangle cut the lines from opposite sides, the direction of the resulting currents in them is opposite. In the lower limb, *e f*, the direction is from front to back, and in the upper one, *c d*, from back to front. Both currents, therefore, pass round the coil in the same direction. The side limbs of the rectangle—that is, *c e* and *d f*—simply slide, or slip, through the lines of force, and do not *cut* them; they, therefore, have no current induced in them, and, while adding to the resistance of the loop, are useless, except for the purpose of completing the electrical circuit. The student may now, with advantage,

FIG. 117.



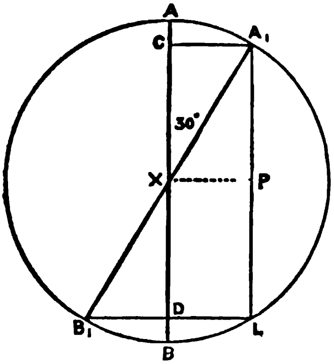
again read the paragraph in Chapter IV. which indicates how the direction of an induced current can in every case be predicted. In the present case the lines of force go from left to right, and the number cut by each limb, so far, is half the total number originally passing through the rectangle.

When the rectangle is turned through another 90°, so that the limb which was at first uppermost is now at the bottom, it has the maximum number of lines of force suddenly thrust through it again; another induced current is the result, and as, during the movement, both the horizontal limbs cut the lines from the same side as they did in the first movement—that is to say, one limb still cuts downwards and the other still cuts upwards—the direction of the current is the same as that developed during the first quarter of a revolution. Further, as the number of lines of force cut is in each case the same, the induced E.M.F. is also the same, provided the rates of moving are equal.

If, therefore, the rectangle is rapidly turned at one sweep from its original position in fig. 117 through 180°, a current will be induced, in the direction shown by the arrows, during the whole of that movement. If the rotation is continued, on passing the 180° the horizontal limbs again begin to cut the lines of force, but they then cut them from their opposite sides, or in the opposite direction to that during the first half-revolution. The resulting current is therefore in the opposite direction to the previous one, but of precisely the same strength if the motion is uniform. A continuous rapid rotation of the rectangle then, will give rise to a series of currents alternating in direction, two distinct currents being generated during each complete revolution, the reversal taking place every time the rectangle passes the points at which its plane is at right angles to the lines of force.

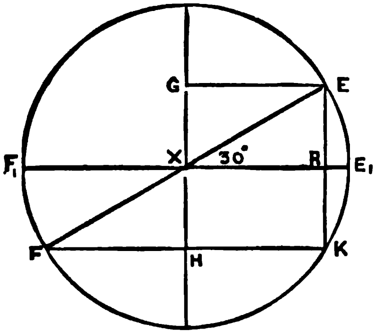
Supposing both the field and the speed of rotation to be uniform, the question arises whether the E.M.F. is also uniform during, say, the whole time of a half revolution. As the induced E.M.F. is proportional to the *rate* at which the lines of force are cut, it is only necessary, in order to decide this question, to ascertain whether the rate of cutting is, under the circumstances, also uniform. A little reflection will show that just when the rectangle begins to move from its position in fig. 117 it is *cutting* hardly any lines at all, but that its horizontal limbs, like the vertical limbs, are rather sliding along or slipping through them, and therefore at the beginning of the movement the rate of cutting, and consequently the E.M.F., is comparatively low. But when the rectangle has turned through about 90°, it is cutting the lines almost at right angles; there is practically no sliding whatever, and the rate of cutting, and therefore also the E.M.F. produced, is much greater—it is, in fact, at its maximum. This gradually decreases until, when near the 180°, the E.M.F. is again at a minimum, and the reversal takes place.

FIG. 118.



A reference to fig. 118 will make this clearer. A B represents the coil viewed end on in the vertical position; X the axis of rotation, and A_1 B_1 the position of the coil after it has been turned through 30°. Clearly the number of lines cut by the top limb of the coil are those enclosed in the space A C, and by the bottom limb those in the equal space B D. Therefore the total number cut during this movement of the coil may be represented by the sum of these two lines A C + B D.

FIG. 119.



Now in fig. 119, E F represents the position of the coil after it has been turned through 60°; if from this point it rotates through an other 30° its position is represented by E_1 F_1, the lines of force out during this movement being all those included in the space E K. now E K is considerably greater than A C + B D, and therefore, as the field is uniform, the coil cuts a much greater number of lines of force by moving through 30° when its plane is nearly parallel to the direction of the lines than it does by moving through an equal angle while it is nearly perpendicular to them. But as the speed of rotation is uniform, it takes precisely the same time to pass through these equal angles, therefore the rate of cutting, and consequently the E.M.F., must be much greater in the former than in the latter case. In fact, the rate at any moment is proportional to the *sine* of the angle through which the coil has then moved from the vertical position.

We have defined a magnetic field of unit strength to be one having one C.G.S. line of force per square centimetre, and if a conductor one centimetre in length is moved transversely through this field at a velocity of one centimetre per second, it will cut one line of force per second, and thereby develop one C.G.S. unit of electro-motive force. If either the strength of field, the velocity, or the length of wire be doubled, the resulting E.M.F. will be doubled, the number of lines cut per second being increased two-fold. If we simply know the number of lines of force cut per second, the E.M.F. can be calculated without any consideration as to the length of conductor or strength of field. If the field is not uniform, however, or if the wire moves at a varying speed, the rate of cutting, and therefore the E.M.F., will fluctuate. But the *average* of this fluctuating E.M.F. will be equal to the average rate of cutting, that is to say, it can be found by dividing the whole number of lines cut by a conductor, by the time in seconds occupied in the cutting. If, therefore, the rectangle in fig. 117 makes one revolution per second, and the maximum number of lines of force embraced by it in the zero position is denoted by N, then each limb will cut 2 N lines per second, because it cuts the whole number N during the downward sweep, and again during the upward movement. Consequently each limb develops an average E.M.F. of 2 N C.G.S. units, and as both limbs are connected in series the total E.M.F. becomes 4 N units. Further, if the rectangle makes *n* revolutions per second instead of only one, then *n* times as many lines will be cut per second, and the average E.M.F. will be 4 N *n* units. But since the C.G.S. unit of electro-motive force is so very small, a much greater practical unit, called the volt, equal to 100,000,000 C.G.S. units, is employed. All results obtained in C.G.S. measure must, therefore, be divided by this number to give the value in volts, and the simple equation may be written,

$$\text{average E.M.F.} = \frac{4\,\mathrm{N}\,n}{100{,}000{,}000}\ \text{volts.}$$

It may be mentioned that the value of N is, in actual machines, very high, being, as a rule, several millions. In practice, it is this average E.M.F. which concerns us most, but we may observe that if the rectangle were rotated at a constant speed in a uniform field, the actual E.M.F. being developed at any moment when it had moved through an angle a from the zero position would be

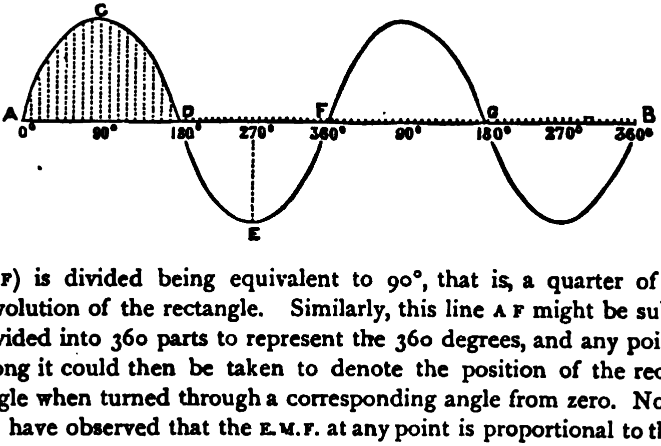
$$\mathrm{E} = \frac{2\pi \sin a\,\mathrm{N}\,n}{100{,}000{,}000}\ \text{volts.}$$

The above refers to the case of two active wires, forming limbs of a rectangle and joined up in series in such a manner that the E.M.F. of one is added to that of the other. The resulting E.M.F. is twice that developed by one active limb; and if the wire were wound in a number of convolutions, it would be necessary to multiply by the number of active limbs then joined in series (instead of by 2, as in the present case) to obtain the total E.M.F.

The function above referred to as the 'sine,' is one with which the student will frequently come in contact. Perhaps, therefore, it will now be as well to explain briefly what is meant by the sine of an angle. If in one of the two straight lines which contain any angle, such as E X R in fig. 119, any point, say E, is taken, and from it a line E R is drawn perpendicular to the other line, a right-angled triangle, E X R, is formed. The length of the perpendicular E R divided by the length of the hypotenuse E X, that is, $\frac{\mathrm{E\,R}}{\mathrm{E\,X}}$, is a definite value, no matter what the area of the right-angled triangle may be, provided the angle E X R is unaltered. And this ratio $\frac{\mathrm{E\,R}}{\mathrm{E\,X}}$ is called the sine of the angle E X R. The sine of any other angle is similarly measured; for instance, in fig. 118 $\frac{\mathrm{A_1\,P}}{\mathrm{A_1\,X}}$ is the sine of the angle $\mathrm{A_1\,X\,P}$. If we always choose the same length of line for the denominator, as will be the case if it forms the radius of the same or equal circles, as E X and A_1 X, and let it be equal to unity, then the sine is simply measured by the numerator E R or A_1 P, that is, by the length of the perpendicular. When the angle becomes very small, the perpendicular, and therefore the value of the sine also, becomes very small ; in the case of the imaginary angle 0° the perpendicular disappears, the sine of 0° being 0. When the angle is 90° the perpendicular coincides with and is equal to the radius. The sine of 90° is therefore 1, and this is the highest possible value of the sine. It decreases as the angle further increases, until, at 180°, its value is again 0. From here it is reckoned as negative, the sine of 270 being — 1. By referring to a table such as that on p. 98 the value of the sine of any angle can readily be found, and we can, therefore, calculate the relative value of the E.M.F. at any position of the rectangle, and also show diagramatically how the E.M.F. should rise and fall in a perfectly uniform field.

In fig. 120 the portion A F of the horizontal line A B represents a circle straightened out, each of the four equal parts into which it

FIG. 120.



(A F) is divided being equivalent to 90°, that is, a quarter of a revolution of the rectangle. Similarly, this line A F might be subdivided into 360 parts to represent the 360 degrees, and any point along it could then be taken to denote the position of the rectangle when turned through a corresponding angle from zero. Now we have observed that the E.M.F. at any point is proportional to the sine of the angle through which the coil has then turned from zero; and it is convenient to take a number of points along this line, and at each of them erect a perpendicular proportional in length to the sine of the angle which that particular point represents. During that half of the revolution in which the sines are reckoned as minus, the perpendiculars should be drawn below the line, indicating the reverse direction of the E.M.F. and current. For instance, at 90° the sine will have the greatest value, viz. unity, while at 45° the perpendicular will be only 0·707 of that at 90°, because the sine of 45° is 0·707; at 270° the sine is − 1, and therefore the perpendicular equal in length to unity is drawn below the line.

By joining the extremities of these perpendiculars we obtain a curve known as a sine curve, which at a glance indicates the manner in which the E.M.F. rises and falls during one complete revolution of a simple coil; and the whole of the curve from A to B shows the fluctuation of the E.M.F. during two revolutions.

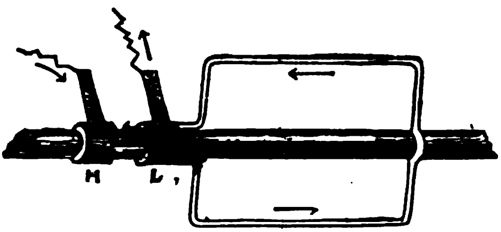
If in fig. 119, EX is taken as unity, it may represent the height of C or L, the highest points on the sine curve, and then EG will be the length of the perpendicular representing the electro-motive force at 60°, for EG is the sine of the angle EXG, which is the angle (60°) through which the coil has turned from the vertical position. Similarly, A_1C (fig. 118) will represent the E.M.F. developed when the coil has turned through 30°, for A_1C is the sine of that angle.

The curve (fig. 120) shows that the E.M.F. at 90° is equal to that at 270°, but that it is positive in the one case and negative in the other.

Referring again to figs. 118 and 119, we observe that the 'effective area' of the coil, with respect to the lines of force which it embraces in the position A_1B_1, is proportional to A_1L, and in the position EF to EK—that is, A_1L and EK are proportional to the number of lines of force passing through the coil in the two positions. Now, $\frac{A_1L}{A_1B_1}$ is the cosine of the angle through which the coil has already rotated, for the angles A_1XA and PA_1X are equal, or it is the sine of the angle which the coil makes with the direction of the lines of force; as is also $\frac{EK}{EF}$. Taking, for simplicity, the equal lengths A_1B_1 and EF as unity, we see that the number of lines of force passing through the coil in any position in a uniform field is proportional to the cosine of the angle through which it has been turned from its position at right angles to those lines, and also to the sine of the angle which it makes with the lines of force.

These variable alternating currents, depicted in fig. 120, being thus developed by the rotation of the wire rectangle, some device is required to enable us to lead them away to an external circuit and there make use of them. The rectangle might, for this purpose, be mounted on a wooden spindle (fig. 121), and its ends connected to two flat metal rings, H L, fixed a little distance apart on the spindle, contact being then made by means of a flat spring, or a wire brush, pressing against each of the rings. By attaching wires to these contact brushes the currents can be conducted away to any desired point.

FIG. 121.



It remains now to show to what extent, in practice, we can comply with the conditions which theory teaches us will tend to make the E.M.F. high.

For a small machine, permanent magnets may be used to supply the field, and for this purpose a horse-shoe magnet is found to be very convenient but it should be bored out or fitted with soft iron cheeks, of such a shape that there is just sufficient room for the wire coil to rotate between them. The steel should be strongly magnetised, and if of considerable size, it should be laminated, or built up, of a number of these magnets with their like poles adjacent. A circular magnet (fig. 122), divided at one part of the circle, and with just sufficient space bored out for the coil to rotate is better than one of the ordinary horse-shoe pattern, although not so easy to make. Having obtained the magnetic field the next thing is to get as many as possible of the lines of force to pass through the coil of wire. Iron here comes to our assistance once more, for, by winding the rectangle round a core of pure soft iron, we concentrate those lines which would otherwise stray, and the number passing through the wire is greatly increased. It is almost superfluous to add that the actual area of the rectangle should be as great as possible, provided that it is kept within the limits of the field, and since, as we have seen, the induced E.M.F. is proportional to the number of active conductors joined in series, the wire may be wound into a coil consisting of a number of turns instead of only one. Now, a coil in which currents are induced by its movement within a magnetic field is generally called an 'armature.' The core of one of the earliest forms of armature is shown in section at A, between the poles of the circular magnet F, in fig. 122, and although, when criticised in the light of our present knowledge, the design proves to be very faulty, it will serve very well to illustrate the principle. A view of this armature is also shown in fig. 123. It consists of a considerable length of silk- or cotton-covered copper wire, wound in the grooves of a shuttle-shaped piece of soft iron, A B, which is usually about twice as long as its greatest width. It is provided at one end with a driving-pulley, *p*, and at the other end by a device for communicating the current to the external circuit. Good effects can be obtained by rotating such an armature in a strong field. The speed of rotation must be high, but this can readily be obtained by any mechanical multiplying device, such as a pulley of large diameter driving a smaller one on the armature spindle. Although the E.M.F. increases with the number of turns of wire on the armature, it is found that this increase is not by any means proportional,

FIG. 122.

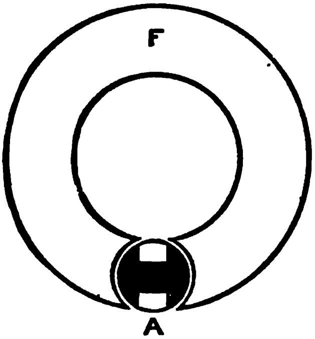
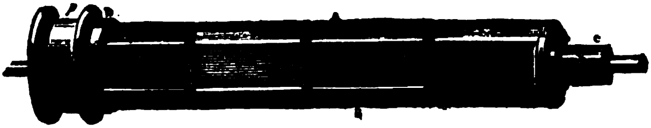


FIG. 123.



especially when the speed of rotation becomes very high. One important reason is because the conditions are very favourable for the 'self-induction' of the armature to make itself evident. We have already seen that this effect becomes very marked with rapidly varying or alternating currents, and since, also, it increases with the square of the number of turns of wire, it is obvious that the number cannot be indefinitely increased with any prospect of satisfactory results. The increase of resistance, though not in itself such an important matter, also limits the length of the wire. It is, therefore, preferable to endeavour to increase the strength of the field and the length of the active limbs of the coil rather than the number of turns.

That the design of the shuttle armature is faulty may easily be proved, for, after being rotated for a little time, the iron shuttle or core gets quite warm. Now, this heat, so developed, represents a definite fraction of the energy expended in rotating the armature, which, as it does not reappear as electricity, is to all intents and purposes wasted. It is an interesting fact that whenever a mass of metal is rapidly rotated in a magnetic field its temperature rises, the heat being the direct result of currents of electricity which are induced in the metal, and which are known as 'eddy' currents. Their initial direction is at right angles to the lines of force of the magnetic field, and also at right angles to the direction in which the mass moves; therefore, in the shuttle armature, they travel lengthways along the iron core, completing their circuit in a more or less circular path in the iron (whence they gain the name of 'eddy' currents), and they follow the general law in reacting upon the field in which they are produced, in such a manner as to tend to stop the motion of the moving body. The E.M.F. of these currents is not high, but as the mass of the metal is great, and its resistance therefore small, the currents are sufficiently strong to considerably raise the temperature of the metal. In fact, it is possible to melt a piece of a metal which fuses at a low temperature, by simply spinning it rapidly in a very strong field.

It is evident that such a certain sign as this, that energy is being wasted, must not be ignored, and, since we cannot stop the tendency for the currents to be produced, the only alternative is to put difficulties in the way of their production.

In the case in question, the best method is to 'laminate' the armature, or to build it up with a number of small discs cut to the required shape and bolted together, instead of using a solid piece of iron. The iron must be continuous in the direction in which the lines of force have to pass through it, otherwise the efficacy of its action in concentrating these lines would be seriously impaired, while it must be discontinuous in the direction in which the eddy currents tend to flow, viz. at right angles to the lines of force. To meet these requirements the discs threaded on the spindle must be well insulated one from another, although, on account of the low E.M.F., a sheet of thin paper or a layer of varnish is, as a rule, sufficient. It is hardly necessary to adopt this precaution in the kind of machine we have been considering, which is very small, and only made to be driven by hand-power, but it becomes absolutely necessary, as well as economical, in the larger machines driven by steam-power. At first sight it would appear, remembering that the E.M.F. developed in the armature coil varies as the rate at which the lines of force are cut, that the E.M.F. of a magneto-electric machine should be simply proportional to the speed of rotation, the strength of the field being invariable. But there are several causes which tend to prevent the increase of the E.M.F. developed by the augmentation of speed attaining this proportion, the principal being the eddy currents produced in the core, the electro-magnetic reaction of the current in the armature upon the field produced by the field-magnets, and the self-induction of the armature. It is important to notice that when a current is flowing round the armature coil the whole armature is in reality an electro-magnet, and it acts as such upon the poles of the permanent horse-shoe magnet which supplies the field, this reaction, as in every similar case, tending to stop the motion of the armature. If, however, the armature is forcibly rotated against this tendency, the result is that the magnetic field is distorted and dragged somewhat out of its true position, and, as the current in the armature rapidly alternates from zero to a maximum, this dragging effect will also vary considerably, with the result that the field will be kept in a state of oscillation and its uniformity destroyed. The maximum current in the armature becomes higher as the speed is increased, and the distortion of the field is then greater, the result being a tendency to prevent the E.M.F. rising in proportion to the speed. Furthermore, as the iron core has a greater number of lines of force passing through it when the current increases, its permeability may also become appreciably lower.

Besides the waste due to eddy currents, which increases very rapidly with the speed, the effect of the self-induction of the armature also becomes strongly marked, this latter not only preventing such a high E.M.F. being attained, but, in addition, retarding the rise and fall of the current. In fact, were we able to plot a curve showing the rise and fall of a current in this shuttle armature, we should find it somewhat similar to that given in fig. 120, but with the important difference that it would be shifted more or less to the right, its maxima and minima being less in value and occurring later than would be the case if the armature had little or no self-induction. Owing to the fact that it is not possible to construct a practical armature with as little self-induction as the simple rectangle, or to make its active limbs cut the lines of force of a uniform field in such a regular manner as is done by our experimental rectangle, we do not in practice obtain a perfect sine curve for the curve of potentials of any armature, but only an approximation thereto.

We shall presently be better able to consider the reaction on the field in connection with a different type of armature, but we may here remark that it is one of the most important points to be borne in mind in deciding how a more powerful and efficient machine can be obtained. Now, the electro-motive force may be increased in several ways.

1. By increasing the speed of rotation.

2. By increasing the number of turns of wire in the armature, thus increasing the number of active limbs joined in series, which cut the lines of force. This method, as already pointed out, adds not only to the resistance, but also to the self-induction of the armature.

3. By increasing the area of the armature coils, or by making the core more massive, for in either case the number of lines of force cut by the coil is, within certain limits, increased.

4. By increasing the strength of the field.

The last-named method is the freest from objections, and it has the all-important advantage that, the stronger the fixed field is, as compared with that developed by the armature, the less is the reaction and consequent distortion of the field.

The necessity for a strong field is so apparent that powerful electro-magnets are now usually employed, but, as might be expected, in all the early efforts to construct a dynamo-electric machine, the field was obtained by means of permanent magnets. But the method of cutting the 'armature' wires by lines of force was not by any means restricted to the rotation of the armature in the field. One very interesting method was applied by Wheatstone, and is still largely employed, to generate short intermittent and comparatively feeble currents. The wire in which the currents are generated is wound on, let us say, two bobbins (see fig. 124), which are fitted with soft iron cores, as shown by the dotted lines, and placed one on each pole of a powerful permanent steel magnet. Many of the lines of force due to this steel magnet pass through the soft iron cores, and complete the magnetic circuit across the air-space at the top in the well-known curved form, but no current is generated in the wire while they are undisturbed. If, however, a soft iron bar is placed across the ends of the cores and very near to them, as shown in fig. 124, or as shown by the dotted lines in fig. 125, a great many of the lines of force rearrange themselves and pass through this soft iron 'keeper.' In moving to their new positions they cut the convolutions of the coil and generate therein an electromotive force which, if the circuit is completed, gives rise to a momentary current. When the keeper is entirely removed the original arrangement is re-established, and the cutting which then takes place also generates a momentary current, but in the opposite direction to the previous one. The most convenient way of rapidly shifting the soft iron keeper is to mount it on a spindle and rotate it; in fig. 125 it is shown at *a b*

FIG. 124.

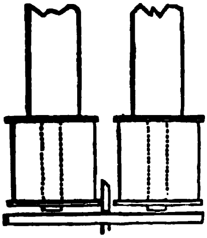
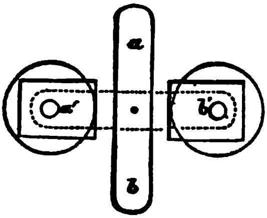


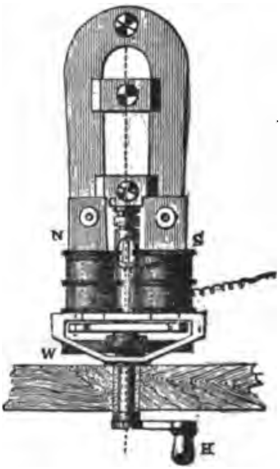
FIG. 125.



in the position at right angles to the line between the two bobbins, while the dotted lines show its other extreme position, a^1 b^1, when it is right over the cores.

In fig. 126, which is a view of a portion of the actual apparatus, this keeper *a b* is shown fixed on a spindle, which also carries a pinion gearing into a larger driving-wheel, W, turned by a handle, H. The keeper can, by means of this arrangement, be rotated with considerable velocity in front of the two bobbins, which, with their cores, are shown fixed to the soft iron cheeks screwed on to the poles of the horse-shoe magnet N S, which is a compound one, being built up of seven thin horse-shoes bolted together. Four coils are usually employed, placed symmetrically, two on each pole; double the number of currents in each revolution are then generated, but the principle remains the same.

FIG. 126.

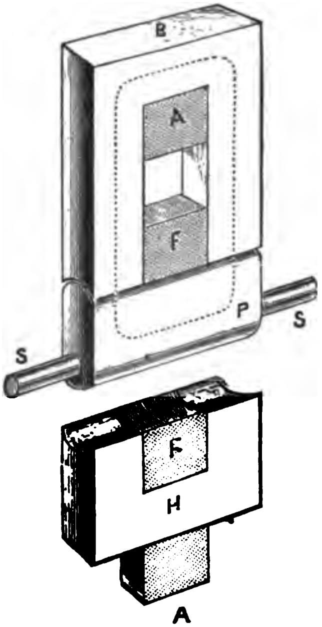


Hitherto no large machines built upon the foregoing principle have been practically used, and this is, perhaps, surprising, as the advantages due to the simplicity of construction are many and important. The only moving part of the apparatus is a mass of iron which, if truly balanced, can be rotated at a very high speed without involving any mechanical difficulties, and as all the coils are fixed, connection between them and any external circuit can easily be made. Mr. W. M. Mordey has, however, described several methods of applying this principle to large machines, and he has constructed a model of one form which certainly appears to be charmingly simple and practical.

The armature and field coils are each wound in the form of a ring of rectangular section, the former being of larger diameter than the latter, and they are placed concentrically, with the field coil inside the armature coil. A number of pieces of iron are placed in such a manner that the rotation of an iron keeper causes many of the lines of force at one moment to embrace both armature and field coils, and at the next moment to pass round the field coil only; and as, during their movement from one position to the other, they cut the armature coil transversely, alternating currents are induced in that coil.

The principle may be more easily grasped by a consideration of the arrangement illustrated in fig. 127, in which F F show the field coil in section at two points at opposite extremities of a diameter, and A A show sections through two similar points of the armature coil. B is a mass of iron which embraces both the armature and field coils, while H is a piece, equal in cross-section but having shorter limbs, which embraces the field coil only, the armature coil being placed outside the yoke. P is a keeper carried by the shaft, S, which can be rotated rapidly, the shaft being at the centre of the two circular coils, F F and A A. If a powerful current is sent through the field coil F F, a large number of lines of force will be developed, and their arrangement will largely depend upon the iron pieces, H and B, but more especially upon the position of the keeper P with respect to H and B.

FIG. 127.

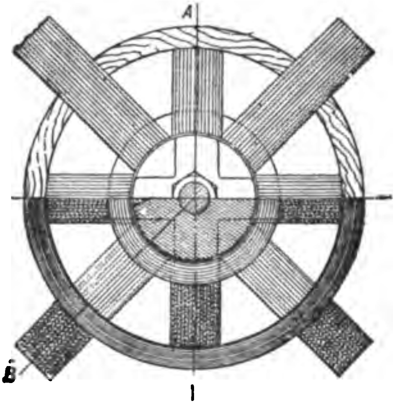


When P is situated as shown in the figure it forms with B an almost complete magnetic circuit of low permeability round both coils A and F, and nearly the whole of the lines generated by the field coil in the vicinity will embrace the armature. In springing into this position (shown by the dotted line), the lines cut the armature coil transversely from the inner side, and give rise to a current, depending in E.M.F. upon the number of lines and the rapidity with which their position is changed. When the keeper is moved away there is a considerable air gap, offering a high magnetic resistance at the ends of the limbs of B, and consequently many of the lines of force collapse upon the coil F, cutting the armature from the outside and generating an E.M.F. in the opposite direction. Not only is the magnetic resistance of the path round the two coils made greater, but as P rotates it reaches a position where it acts as a keeper to the iron piece H, which embraces the field coil only, so that an almost complete magnetic circuit is then formed round the field coil, and nearly the whole of the lines of force pass through H and P and very few extend round A. Therefore, if the keeper P is rapidly rotated the armature coil will be cut by a number of lines of force as they take up new positions, first outside and then inside it. It is evident, however, that it would not be possible to make all the lines of force developed by the field coil take either the one path or the other, many of those surrounding the coil at a distance from the iron being but little affected by the movement of the keeper, but in designing an actual machine care would be taken to so dispose the iron that most of the lines of force would be influenced.

In Mr. Mordey's machine there are four iron pieces similar to B, embracing both armature and field coils, placed 90° from each other as shown in fig. 128. Between these are placed four shorter pieces similar to H, outside the field but inside the armature wire.

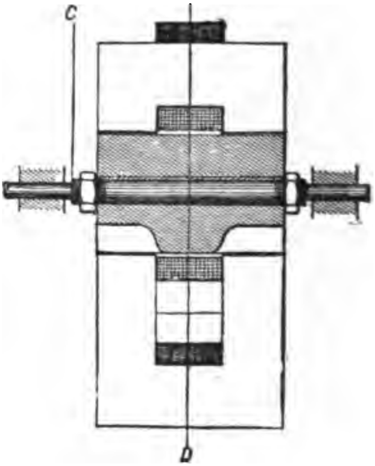
The lower half of fig. 128 is shown in section; fig. 129 is also in section, the upper half from A to the centre of the shaft, and the lower half from the centre of the shaft to B, so as to obtain a section through a short and a long iron limb. The mass of cast-iron which plays the part of a keeper may be described as a cylinder having four deep sector-shaped notches cut at each end. If viewed end-on, a section near one extremity would be in the form of a cross, while a section through the middle would be circular. In the figures each arm of the cross is shown as forming a keeper to one of the smaller iron pieces embracing the inner or field coil only, and consequently few of the lines developed by the field coil extend round the armature coil. In the lower part of fig. 129 the deep notches are opposite the iron pieces which embrace both coils, forming a great break in the magnetic circuit, and this is also shown in fig. 128. On rotating through an angle of 45°, however, the keeper completes the various magnetic circuits in such a manner that most of the lines of force extend round both coils. These two alternate conditions succeed one another rapidly as the keeper continuously revolves. As the lines of force are rapidly carried backward and forward past the armature coil, they generate therein the desired currents, but they also give rise to eddy currents in the masses of iron through which they are projected. The direction in which these eddy currents would be set up is parallel to the currents in the armature core, and therefore the masses of iron should be laminated so as to give discontinuity in this direction, while continuity is retained in the path of the lines of force. Consequently the iron is built up of a number of thin U-shaped sheets, insulated and bolted together.

FIG. 128.



Section through C D.

FIG. 129.



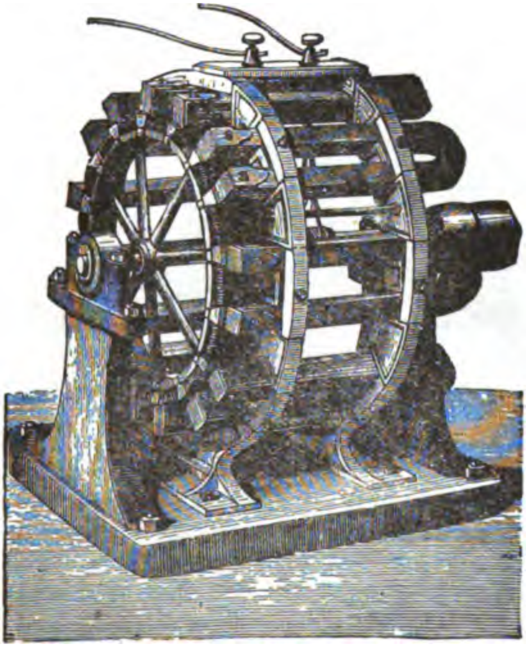
Section through A B.

Machines in which steel magnets are employed for producing the field are often called magneto-electric generators, and are sometimes regarded as a class altogether distinct from machines in which the field is developed by one or more electro-magnets, but such a distinction is altogether arbitrary.

The best and most useful form of so-called magneto-dynamos is that of De Meritens, which is extensively employed for lighthouse purposes. A general view of a simple form of this machine is shown in fig. 130.

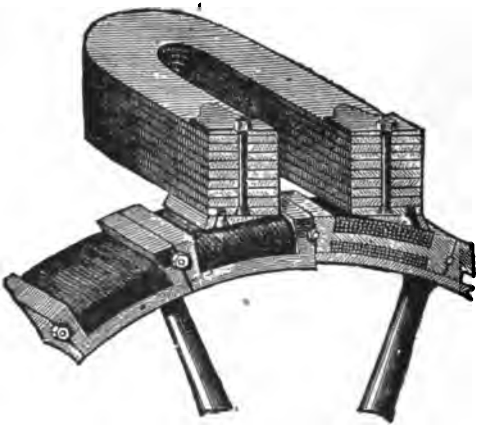
The armature consists of a series of sixteen coils fixed round the periphery of a wheel of brass or other non-magnetic material.

FIG. 130.



The method of constructing and fixing the coils is shown in fig. 131, one coil and a portion of the rim of the wheel being in section. A flat core of soft iron (composed in the more recently built machines of eighty pieces of soft sheet iron one millimetre thick and stamped out to shape) is provided with rather large pole-pieces, and has wound over it about 1½ pounds of copper wire. Each coil is distinct from the others, the cores of two adjacent coils being magnetically insulated (at X Y, fig. 132) by a thin strip of copper. The wheel or frame to which the coils are attached is furnished with a number of substantial lugs. The ends of the pole pieces of the cores are placed between these lugs, and, being provided with semi-cylindrical grooves of the necessary dimensions, the whole are firmly fastened together by bolts. It is important to notice that the extensions of the cores reduce the air-space between the poles of the permanent magnets and the cores to a minimum, and therefore conduce to the projection of the highest possible number of lines of force through the coils and consequently to the generation of the maximum attainable E.M.F.

FIG. 131.



The field is produced by a series of eight compound steel magnets fixed horizontally round the armature ring, by means of a brass framework. The inner surfaces of the magnets are provided with small soft iron pole-pieces, so that the coils in revolving pass as close to the field-magnets as possible. The magnets are disposed uniformly round the ring, the coils passing, therefore, north and south poles alternately.

The distance between the limbs of each magnet being exactly equal to that between the opposite poles of the adjacent magnets, and this distance being also equal to the length of each coil, it follows that, on the armature being rotated, each coil passes sixteen alternate poles in one revolution. The manner in which the currents are induced can best be appreciated by a reference to fig. 132, where the ring has only four coils which rotate between a similar number of magnet poles, N S N S, one coil or segment, A B, being shown in section. When the coils are in the position shown, the minimum number of lines of force is, at that moment, passing through them, but after traversing another 45°, the core-extensions will be opposite the field-magnet poles, and the coils will then embrace the maximum number of lines of force; at this latter point the reversal of the current takes place. The coils being all wound in the same direction and all connected together in series, it is evident that the current in the adjacent coils will be opposite in direction to that taken by the current in A B, as they are passing through fields developed by the south poles. Were the adjacent ends of the neighbouring coils connected together, the currents in the various coils would therefore neutralise each other and no electricity could be urged through the external circuit. This difficulty, however, can be very readily obviated, as will be made evident by a reference to fig. 133. Instead of connecting the adjacent ends of two coils together, the connection is made between their two similar ends, that is to say, the end of the coil A to the left hand is connected to the similar end of B, while the end of B to the right hand is connected to the right-hand end of C, and so on. In this way, although the currents in the various coils are generated in opposite directions, they, instead of neutralising one another, are made to take one common direction through the circuit. This does not, of course, alter the fact that the currrent delivered by the dynamo is an alternating one, that is to say, as the coils advance from one set of magnet poles to the next, the direction of the current in the whole of the coils is reversed, and therefore, also, the direction of the

FIG. 132.

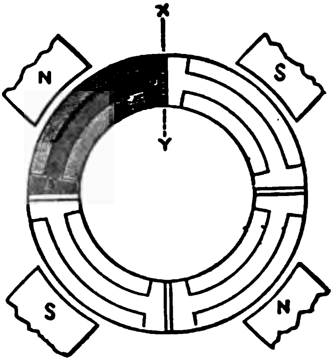
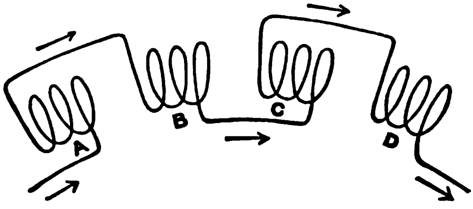


FIG. 133.



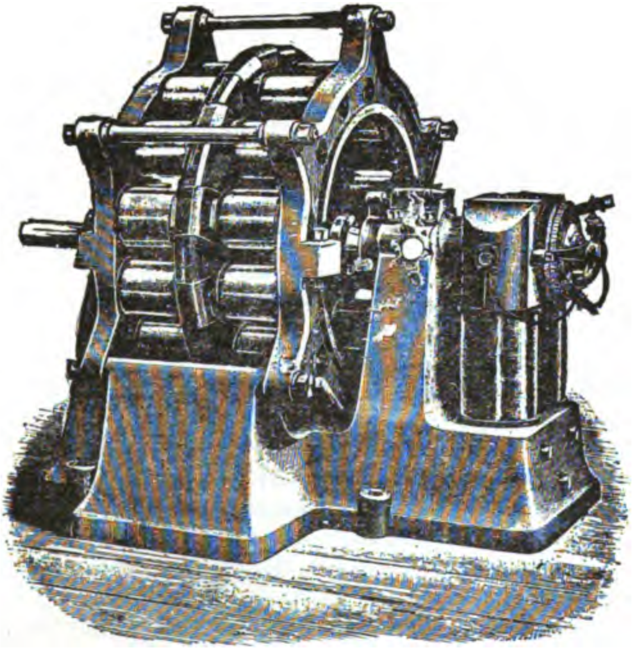
current in the external circuit. The whole of the coils in fig. 130 being joined together in series, the total E.M.F. developed is sixteen times that developed in one of the coils. In the more recent form of this machine there are five armature rings, each with its sixteen coils and eight compound magnets. The latter are, for very apparent mechanical reasons, fixed radially instead of longitudinally, and they have a total weight of about one ton. The eighty coils are divided into two circuits which are brought to four collecting rings mounted in pairs on an insulating bush fixed on the principal shaft of the machine and, therefore, revolving with it. This type is almost exclusively employed for lighthouse purposes, and its E.M.F. varies almost directly with the speed of rotation. It is unusually strong in design, the parts being also fixed together in such a manner as to permit of their being, when defective or injured, very easily removed for renewal or repair.

It has been pointed out that the best means available for increasing the E.M.F. and therefore, also, the strength of the current yielded by a machine, is to increase the strength of the field. Now there is a limit, which is soon reached, to the field obtainable with permanent steel magnets even if built up of thin sections, because the maximum number of lines of force which can be urged through steel is comparatively low, and even then only a portion of this number can be permanently retained, whereas with good soft iron a far greater number can be forced through. If the lines of force are produced by a current circulating in a coil of wire enveloping the iron, the question of retentivity does not arise. Consequently, to develop a given amount of power, a machine in which the field is produced by electro-magnets is considerably smaller than one in which steel magnets are employed.

Primary batteries might be, and in fact were at one time, used to furnish the current for the purpose of exciting the field-magnets, but it is far more economical and advantageous to obtain this current by means of a small dynamo. This auxiliary machine, which we will for the present refer to as the exciter, must be able to excite itself and to yield a current continuous in direction. Descriptions of many such dynamos will be found in the following chapters.

We can scarcely do better, in commencing a study of the modern forms of alternating machines, than describe one which would appear to follow as a natural evolution of the De Meritens. Such a machine, excellent alike in its mechanical and its electrical details, is the one designed by Mr. Gisbert Kapp, and illustrated in fig. 134, which also shows the small exciter mounted on an extension of the main bed-plate, its armature being also fixed on

FIG. 134.



to the main shaft. The field is produced by two crowns of short cylindrical electro-magnets, the cores of which are of wrought-iron $4\frac{1}{8}$ inches in diameter, fixed at one end into cast-iron yoke rings, and provided at their inner ends with rectangular pole-faces, between which the armature revolves. There are twenty-eight of these magnets, fourteen in each crown. Each magnet is wound with 186 turns of thick insulated copper wire, the whole of the coils being joined in series and offering a total resistance of 1·76 ohms. The winding of these coils is such that the magnets forming each of the crowns alternate in polarity, while the opposing faces are of the same polarity. One continuous core is used for the whole of the coils in the armature, and is built up by winding thin band-iron upon a cast-iron supporting ring, the layers being insulated by varnish to prevent the flow of eddy currents. The section of this core is almost rectangular, with its greater dimension radial. The armature wire offers a resistance of 1·8 ohms, and is divided into fourteen coils, wound over the core ring, each coil consisting of eighty turns of insulated wire 120 mils (0·12 inch) in diameter, wound in two layers.

The manner in which the currents are generated as the armature rapidly revolves through the alternate fields is very similar to the method of production in the De Meritens machine. In this case, however, the lines of force enter the armature at both sides of the flat ring instead of at one side only.

The extremities of the armature wire are connected to a pair of brass rings on the shaft, from which the current is collected by copper brushes. As the E.M.F. of these machines is usually high, it is a frequent practice to place the collector-rings on opposite sides of the armature, so that the attendant cannot touch both brushes at the same time.

The machine illustrated is one constructed within the last few months. Before being put into practical use a number of experiments were performed to ascertain its capabilities. On one occasion it was driven at 600 revolutions per minute, and, the exciting current being 9 amperes, the total E.M.F. developed on open circuit was 1,000 volts. When the exciting current was increased to 21 amperes the E.M.F. rose to 2,400 volts. With the same exciting current and the armature of the alternator joined through an external resistance and a dynamometer, a current of 30 amperes was generated, the E.M.F. at the terminals then being 2,000 volts. The available output was therefore 60,000 watts. The power absorbed in exciting the field-magnets was 775 watts, or about 1·3 per cent. of the total output, the loss in the armature due to its resistance being 2·7 per cent.

The cast-iron bed-plate is very substantial, and the method of bolting the yoke-rings to it and to each other is clearly shown in the illustration.

When all the coils are joined in series, the total E.M.F. at the collecting brushes is equal to that developed by one coil multiplied by the number of coils, but occasionally, in such machines, a lower E.M.F. with a heavier current is desired, and then the coils are joined in parallel, either in two sets, or as may be required. An equal E.M.F. might, of course, be obtained with fewer coils and pole-pieces, provided the number of lines cut in the same time and the number of convolutions in series is made the same; but the great advantage accruing to the use of a large number of pole-pieces and coils is that a rapidly alternating current can be obtained without rotating the armature at an enormous speed, and so introducing mechanical difficulties.

It ought perhaps to be explained here that the current, or rather currents, resulting from one complete rotation of a coil in a simple field, which may be represented by the curve A C E F in fig. 120, is called an 'alternation,' and any similar pair of currents developed by any armature with any field is also called an alternation. In estimating the rapidity with which a current is reversed, it is better to speak of the number of such alternations which take place in a second, rather than the number of reversals. The majority of the machines at present in use work at from 80 to 100 alternations per second, and to obtain the latter number a single coil in a single field would have to be driven at 6,000 revolutions a minute. But although a rapidly alternating current can be easily obtained with a large number of pole-pieces, a disadvantage results from the fact that these pole-pieces alternate in polarity all round each crown. Each pole-piece is flanked on either side by others of opposite polarity, and a very large percentage of the lines of force leak across between adjacent limbs, instead of passing through the armature core, and are wasted, since they cannot be cut by the conductor. This defect also exists in the two machines next to be described, where the armature contains no iron.

The form of alternating current dynamo constructed by Siemens is illustrated, together with its exciter, which is driven, independently, from the main shaft, in fig. 135. The field-magnets present an appearance similar to that of those in the Kapp machine, consisting, as they do, of two opposing crowns of cylindrical electro magnets, but with the essential difference in the winding that the

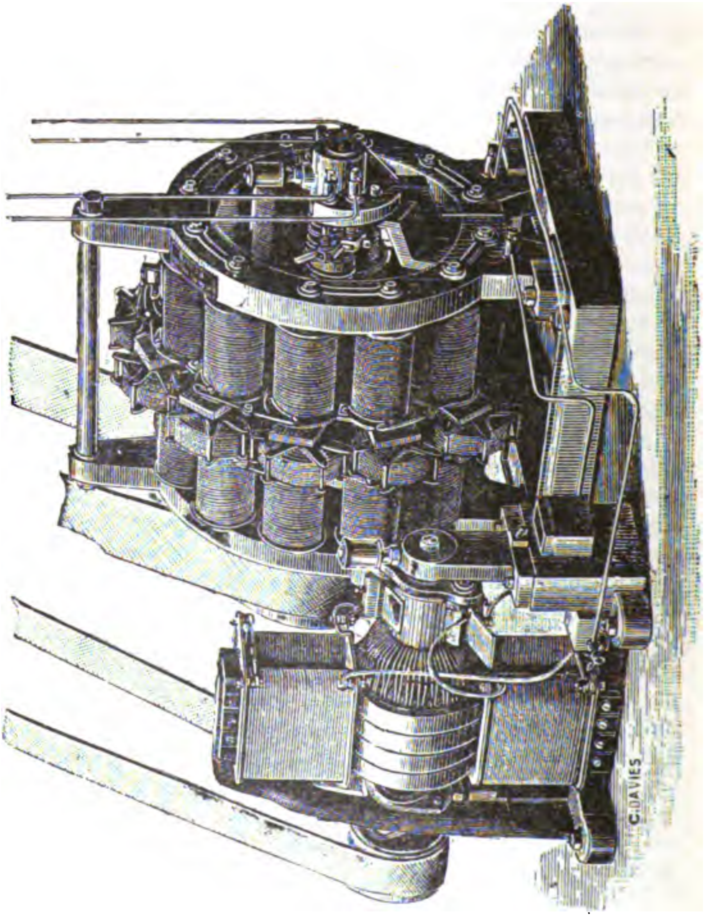
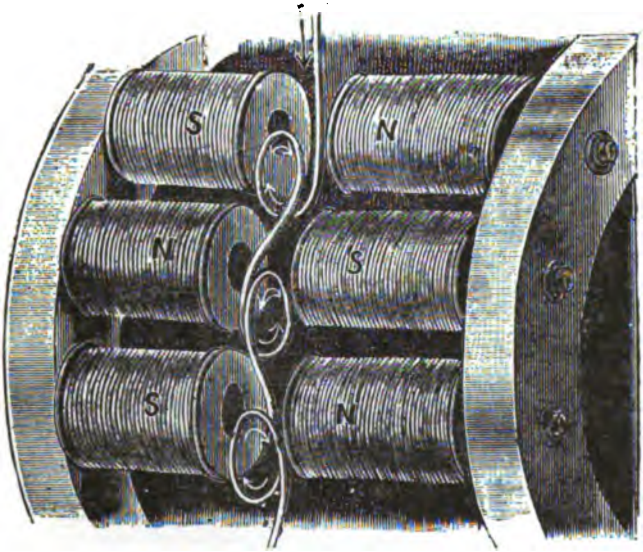


FIG. 135.

facing pole-pieces are of opposite polarity. The adjacent pole-pieces on each frame resemble the Kapp in being also of opposite polarity. The arrangement is clearly indicated in fig. 136, which shows three pairs of magnets and three ideal armature coils, and it will be evident that, with this disposition, the lines of force pass from pole to pole, straight across the armature space. The plane of the armature coils is coincident with the plane of rotation, so that the coils, in rotating, cut through a series of powerful fields with the lines of force alternating in direction. As through any adjacent pair of coils the direction of the lines of force is opposite, it is

FIG. 136.



necessary, in order to prevent the current induced in one coil neutralising that induced in the other, either to make the connections as in the case of the De Meritens (fig. 133), or to wind the bobbins as right- and left-handed helices alternately, after the manner shown in fig. 136. The number of armature coils being the same as the number of fields, it follows that all these coils are, at any particular moment, equally active. Referring to fig. 136, in which the direction of rotation is left-handed, it will be seen that the coils are just leaving the pole-pieces, and currents are being gene rated in the directions indicated by the small arrows. The E.M.F. increases until the coils arrive at positions midway between the pole-pieces, where it is a maximum, because at that moment the forward half of each coil is cutting lines of force in one direction and the rear half in the other direction. And the induced currents, flowing outwards in one half and inwards in the other, coincide in direction round the coil. Every line of force then cut by the coil is being usefully employed. When this middle position is passed, the number of lines cut by the front half increases, while the number cut by the rear half decreases, and this continues until both halves of the coil are cutting lines of force which are all in one direction. Consequently, an opposing E.M.F. is induced in the rear half, the value of which increases until the coil is exactly opposite the pole-pieces, when both halves will be cutting an equal number of lines of force, which are all in the same direction; whence equal and opposite E.M.F.'s will be induced in the two halves of the coil, thus neutralising each other. At this point, then, the reversal in the direction of the current takes place, for, on passing forward, the front half of each coil is cutting less, instead of more, lines of force than the rear half. The number of alternations in each revolution corresponds, therefore, with the number of coils, or, what is the same thing, with the number of fields.

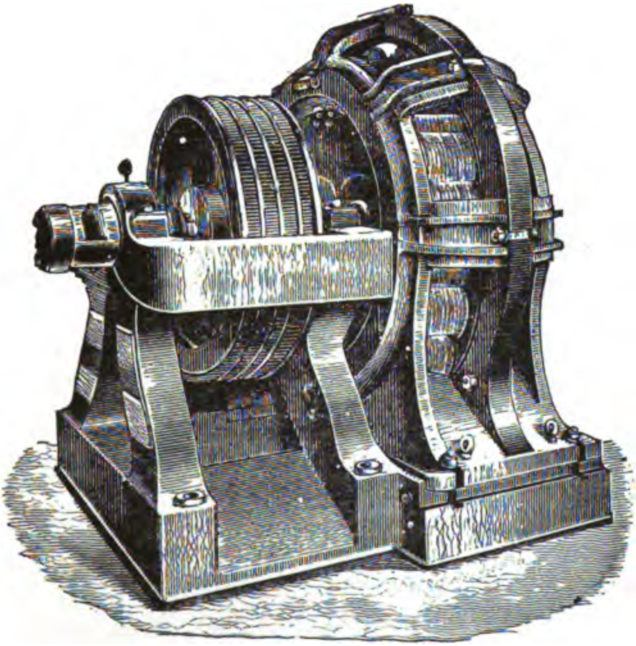
In practice, the machine is built up on a cast-iron bed-plate, to which are securely fixed two circular frames, united and held in position by a stout iron stay. An equal and even number of electro-magnets is fixed to each frame, the cores being turned down so as to fit into holes drilled through the frames. These ends are likewise tapped, and, nuts being screwed on on the outside, the electro-magnets are fixed firmly in position. The inner ends of the cores are furnished with radial pole-pieces, to concentrate the fields and increase the number of lines of force passing through the rotating armature coils.

The armature is fitted up by attaching the coils, which are wound over wooden cores, round the circumference of a disc or wheel which is mounted on the shaft. The coils, instead of being circular, like those in fig. 136, are pear-shaped.

A general view of the latest form of machine designed by Mr.

S. Z. de Ferranti, is given in fig. 137, the particular one illustrated being constructed to develop 150 electrical horse-power. The field-magnets are similar in principle to those in the Siemens Alternator, and consist of two sets of electro-magnets, attached to massive iron rings forming the yokes, the magnetisation of the pole-pieces round each ring being alternately north and south, and the facing pole-pieces also of opposite polarity, so as to develop a series of very powerful fields, alternating in direction. The framework carrying each crown, or ring, of field-magnets is divided vertically into two halves, which, on being unbolted, can be slid out of position in a direction at right angles to the shaft, and so afford access to the interior for cleaning or repair. It may be mentioned that in larger machines at Deptford a small steam-engine is specially provided for the purpose of withdrawing the field-magnets when necessary.

FIG. 137.

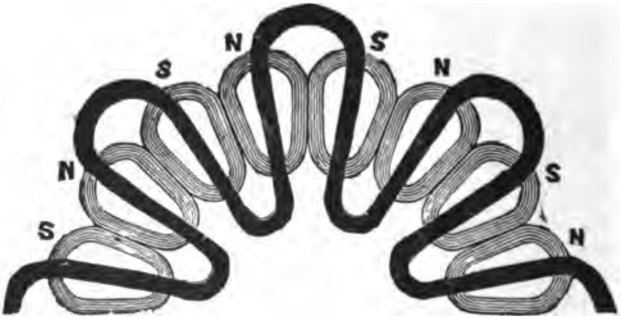


The machine is driven by rope gearing, the pulley being grooved for the purpose.

The method of securing the cores of the magnets to the yoke-rings is unique. The wrought-iron cores of half the magnets forming each crown are fixed in a mould, and the half of the yoke-ring is then cast on to them, making in that way the surest and simplest form of magnetic connection between the wrought- and cast-iron sections of the field-magnets.

The great feature of the original Ferranti machine consisted in the construction of the armature, which is illustrated in fig. 138. The heavy zigzag line represents half of the armature, which consists of a copper ribbon bent round and bolted to a non-magnetic framework attached to the shaft. The faces of one set of field-magnets are shown behind the armature strip, and it will be seen that the space occupied by each complete bend in the armature is equal to that of two field-magnet coils, the distance between two straight radial portions being equal to the width of one coil. When the armature is rotated all the radial portions of the strip are usefully employed in developing E.M.F. At any particular moment each of these portions is cutting lines of force in a direction reverse to that of its immediate neighbours. Consequently, opposite currents are generated in adjacent radial portions, but the zigzag winding naturally makes all the simultaneously generated currents travel round the armature in one common direction.

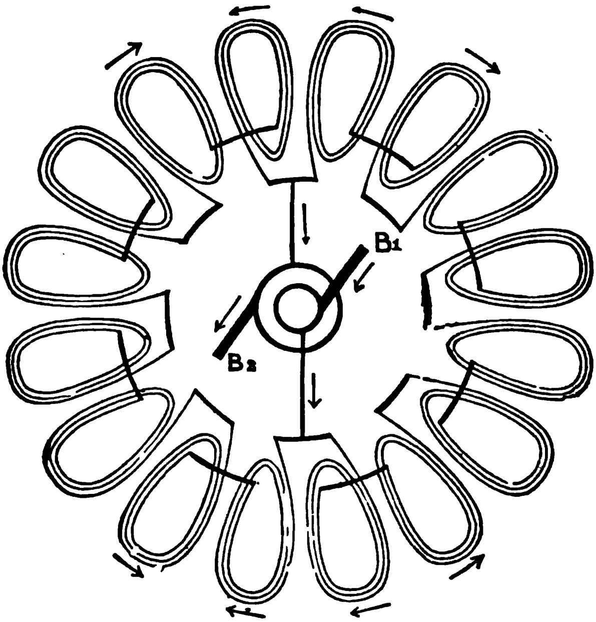
FIG. 138.



Alternate current machines being usually required to develop a high electro-motive force, such a simple winding is of little service, although it answers the purpose admirably when only a low electro-motive force is required. The E.M.F. developed is, of course, proportional to the actual number of the straight radial portions of the armature wire which cut the lines of force transversely. It is manifest that to greatly increase this number in a simple zigzag form would be impracticable, from the fact that the number of field-magnet bobbins must always be twice that of the loops in the armature. The practice, therefore, is to coil the copper ribbon several times round a number of non-magnetic, pear-shaped bobbins. Then, if the whole of the bobbins are connected in series, the total E.M.F. developed will be equal to the E.M.F. of one multiplied by the total number of bobbins. But it is no unusual thing for a machine to develop an E.M.F. of several thousand volts, and, were this method of joining-up adopted, serious difficulties in maintaining insulation would arise at the two ends of the series where connection is made with the external circuit, owing to the fact that there the potential difference between the two adjacent coils would be the maximum developed by the machine. Consequently, the armature coils are always grouped in parallel sets, generally two, as shown in fig. 139. By the arrangement here illustrated, the potential difference between any two adjacent wires can never be more than that developed in one bobbin, but the total E.M.F. of the machine is reduced to half of what it would be, were the whole of the coils joined in series. Fig. 139 shows very clearly the way in which the coils are joined together. Since the current is induced in the opposite direction in adjacent coils, it becomes necessary to connect alternately the two inner and the two outer ends of the coils together, otherwise the E.M.F. of one coil would neutralise that of its neighbour. The currents generated alternate rapidly, but the arrow-heads indicate the direction which the current takes at one particular moment. B_1 and B_2 are the brushes connected to the external circuit, by means of which the currents are conveyed from the insulated metallic rings on the armature shaft.

There are at the Grosvenor Gallery Station two Ferranti dynamos, each of 625 horse-power, and a few details concerning them will be instructive. The mean diameter of the armature is 7 feet, and it comprises 40 coils, joined up in two sets of 20. The copper ribbon is 12·5 millimetres wide, and 0·75 millimetre in thickness, twenty-five turns being wound over a core of brass (insulated with asbestos) to form each coil, the convolutions being insulated by means of a continuous strip of fibre, 0·5 millimetre thick, wound on with the copper. The inner end of each coil is connected to the brass core, these cores being also electrically connected together in pairs, as indicated in fig. 139. In a somewhat similar manner the outer ends of the coils are connected together in pairs through the supporting framework.

FIG. 139.



The peripheral velocity of the armature is 6,050 feet per minute, and, manifestly, special attention has to be paid to the method of fixing the coils to prevent their flying out.

The external potential difference developed is 2,400 volts, but by the adoption of the device shown in fig. 139 the maximum potential difference between the wires on neighbouring coils is re-

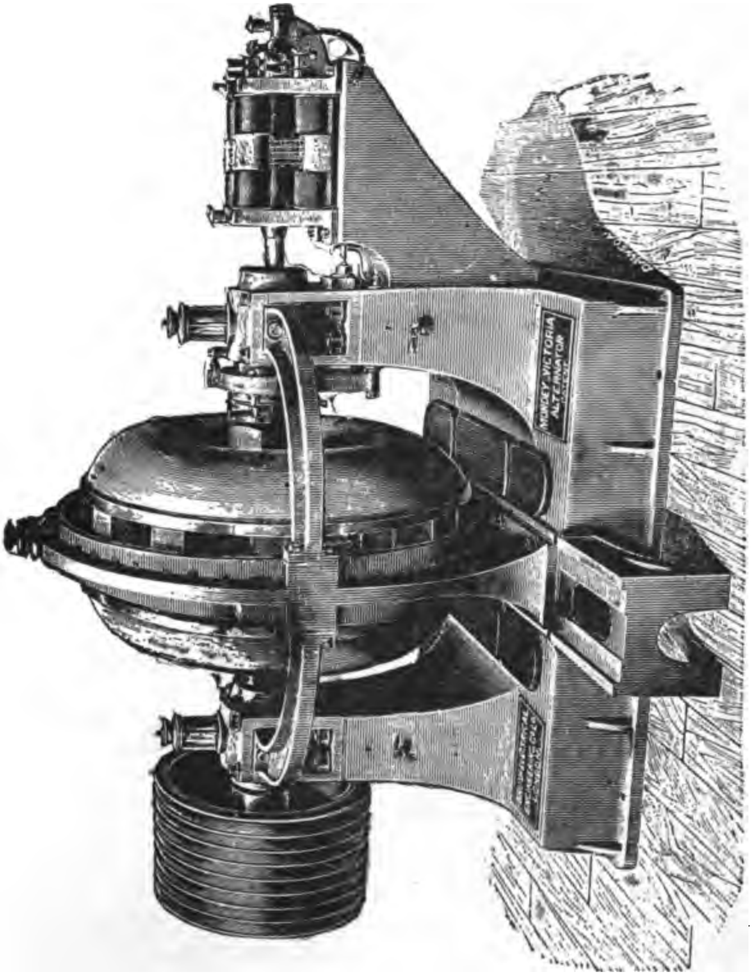


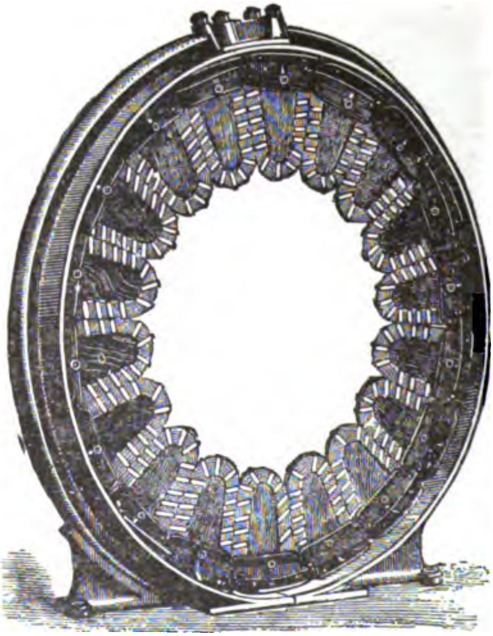
FIG. 140

duced to 120 volts. The resistance of the armature from brush to brush is 0·176 ohm.

The field-magnets are excited by a separate dynamo, twelve electrical horse-power being thus absorbed. There are 80 bobbins on each yoke-ring. The distance between the faces of opposite pole-pieces is only 0·875 inch, which is one of the important advantages pertaining to this form of armature; for the nearness of the opposite pole-faces reduces the wasteful leakage between adjacent pole-pieces.

One of the most interesting and most important machines of recent construction is that designed by Mr. W. M. Mordey, and illustrated in fig. 140. We have in this machine two departures from the practice adopted in constructing the machines previously described. In the first place, the armature is fixed, and the field-magnet rotated; and, in the second place, the lines of force in the various fields projected through the armature coil are all in one direction, the pole-pieces on one side of the armature being all of north polarity, and those on the other side of south polarity. The waste of exciting power due to leakage between adjacent pole-pieces is therefore eliminated.

FIG. 141.

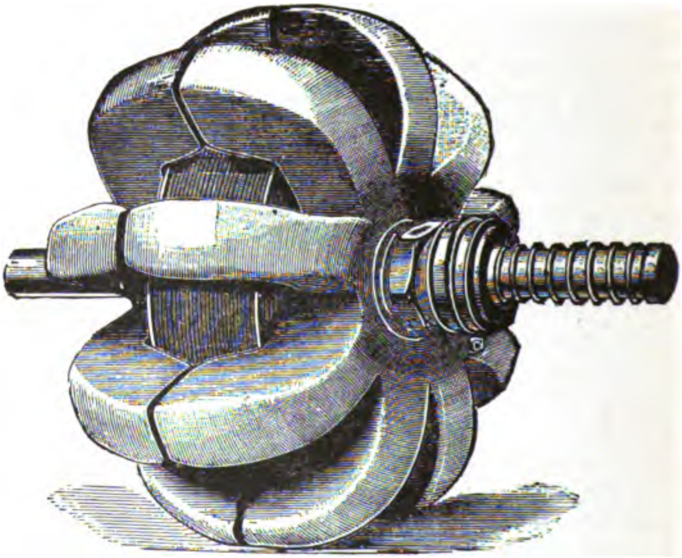


The armature, which is shown in fig. 141, consists of a number of coils of copper ribbon, wound on cores of paraffined wood or other non-conducting material, the different layers or turns of ribbon being insulated one from another. and the whole of the turns in each coil bound together with strips of prepared tape. Each coil is bolted at the outer or broad end between two brackets, the ends of the conductor being brought out through porcelain insulators. The brackets, being bolted to the large gun-metal supporting ring, are securely and rigidly held in position, and the metal supports, which do not anywhere come between the poles of the field-magnets, are almost entirely beyond the magnetic field. In this way the generation of wasteful eddy currents is reduced to a minimum, any slight loss that might arise from this cause being still further reduced by the employment of German silver for the brackets and bolts, as the high resistance of this alloy prevents the generation of any but exceedingly feeble currents. The gun-metal supporting ring, which is bolted to the bed-plate of the machine, is in two portions, being divided in a vertical diametrical line. These two parts, after having received the coils, are bolted together and to the bed-plate, the field-magnets being, however, previously placed in position. By this device single coils, should they become faulty, can be easily and quickly removed for renewal or repair; or each half of the armature can be removed without difficulty by sliding it on to the stool shown in the figure.

The shape of the field-magnet is most remarkable, and differs altogether from that of any other machine yet constructed.

It consists of a single electro-magnet built up in the following manner: A short cylinder of iron, through the axis of which the shaft passes, forms the core of the magnet, and is wound with the exciting coil. To each end of this cylinder or core is attached a massive iron casting of peculiar form, which will be best understood from fig. 142. Each casting consists of a number of horns or claws, which bend over from their common junction, so that the extremities of the two sets of pole-pieces approach within a very short distance of each other, the narrow polar gap or slit thus formed being only just wide enough to contain the armature coils without touching them when the entire field-magnet is revolved. The ends of the 'exciting' coil (which is to be seen inside the pole-pieces in fig. 142) are connected to collector-rings on the shaft, as shown at C to the right of the figure. These might be dispensed with, and the exciting coil, as well as the armature, might be made stationary. The core and its pole-pieces would then be the only portions revolving, and the electrical effect would be the same, but serious mechanical difficulties would arise in fixing the coil. Hence, it is far preferable to attach it to the rotating cylinder. The simplicity of this form of field-magnet is one of its great features, as a single exciting coil suffices for a machine of any size, speed, or number of alternations. The hea rotating field-magnet acts very efficiently as a fly-wheel, and

FIG. 142.



ensures safety and steadiness of running, effectually neutralising, within certain limits, any pulsations due to irregularity in the stroke of the engine. Further, as the parts revolving at the highest velocity are simply solid masses of iron of the strongest description, the electrical and mechanical considerations which usually render low speed advisable do not apply here. The insulation of the armature coils is also simplified, and being stationary they need only to be supported with a view to resisting the drag of the field. The armature is held in its vertical position by substantial horizontal brackets bolted on to the bearing-standards.

The method of joining the armature coils together is similar in principle to that illustrated in fig. 139, the inner ends of the coils being joined together by short copper rods on one face of the frame, and the outer ends on the other face. The position of one of these sets of connecting wires or rods can be seen in fig. 141. The number of alternations during each revolution is the same as in the case of a Siemens or a Ferranti machine having an equal number of armature coils, although the number of pole-pieces is reduced to one half. This arises from the fact that the current in each coil is reversed at that moment when it is between two opposite pole-faces, and again when it is midway between two adjacent pairs of pole-pieces—that is to say, at the moment when it has the maximum number of lines of force thrust through it, and again when it embraces the minimum number.

Since the armature coils are similar as regards shape and the length of ribbon wound on them, and as the various fields projected through them are at any moment equal, the E.M.F. of any one coil is an aliquot part of the whole; and, as all the coils are fixed, the E.M.F. developed in any one coil can be easily measured, and the gross E.M.F. deduced therefrom. As the range in a single coil is usually from 100 to 150 volts, an ordinary voltmeter, such as the Cardew, can be used for the purpose, whereas, to measure the total potential difference directly, an exceptionally high resistance voltmeter, or an electrometer, would be required. The machine is therefore fitted with a special pair of voltmeter terminals, connected to the ends of one coil, for the purpose of making this measurement.

Another point in favour of this machine is that the arrangement of the armature coils can, if required, be readily altered to vary the E.M.F. and current developed. For example, if it were required to reduce the E.M.F. of a 2,000-volt machine to 1,000 volts, this could quickly be done by dividing the armature coils into two sets and joining them together in parallel, the machine being then capable of developing twice the current strength. In any case the total electrical output, or the energy developed, would be the same.

The machine illustrated in fig. 140 is the latest pattern of the Mordey Alternator. In the earlier machines, copper dishes were attached outside the cast-iron claws of the field-magnets, for the purpose of reducing the amount of air-churning which would otherwise occasion loss of energy. The claws, in fig. 142, are shown without these dishes; in the newer form of the machine they are dispensed with, the claws being simply webbed together in the casting, when they present the appearance shown in fig. 140.

The field-magnet is excited by the current from a small Victoria direct-current dynamo, which is mounted on a bracket projecting from the main bed-plate, its shaft being coupled direct to the alternator shaft, so that the two machines are driven together.

A long thrust-bearing is employed to prevent end-play, since the space between the pole-faces and armature is very small, and it is adjustable longitudinally, for the purpose of enabling the field-magnet to be symmetrically disposed with regard to the armature. The armature terminals are placed on the upper portion of the gun-metal supporting ring.

The machine, when driven at 500 revolutions per minute, is capable of developing 75,000 watts, or 100 electrical horse-power, at an E.M.F. of 2,000 volts. 900 watts are required for the purpose of exciting the field-magnets. On account of there being no iron in the armature, and the attention devoted to small details such as the use of German silver for the coil-fittings, the waste of power due to eddy currents is very small: and this loss, added to that due to friction, which, owing to good mechanical construction, is also very low, amounts to but 5 horse-power, that being the power required to drive the machine at full speed on open circuit (or when the armature is disconnected), the field-magnets being excited to their maximum.

In many cases the output demanded from a dynamo varies considerably at different times. For instance, twice as much power may be required to supply lamps at one time as at another.

It is not economical to use one large machine, capable of meeting the maximum demand, and run it to give a small output at other times. but, fortunately, it is possible to join up two (or even more) alternating-current dynamos so as to feed the same circuit simultaneously when required, switching out and stopping one when the other is able to meet the low demand

The armatures must not be joined up in series, but in parallel, and the machines may be driven by belts from the same shafting, or, if necessary, from independent engines running at about equal speeds. In practice the latter course is usually adopted, since it is bad economy to employ a large engine to develop the power required by a small machine.

But parallel working is only practicable when in both machines the rates of alternation are equal, and the alternations 'co-phasal'—that is, when their maximum and likewise their minimum E.M.F.'s occur simultaneously. It is most remarkable that well-designed machines can correct each other and maintain this synchronism; but, as a most important part of the interaction depends upon the 'motor' properties of a dynamo, further consideration of the question must be deferred until electric motors have been dealt with.

CHAPTER IX.

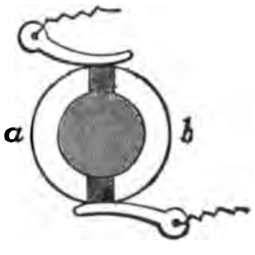
DYNAMO-ELECTRIC MACHINES (DIRECT CURRENT)

ALTHOUGH the sphere of usefulness for alternating-current dynamos has largely increased of late years, there is still a vast amount of work which such machines are, and always will be, wholly incompetent to perform. This is notably the case in connection with the deposition of metals by electricity, and in the 'charging' of secondary batteries. For these, and several other important purposes, it is essential that the current should be continuous, and flow in one direction only. It is possible to arrange matters so that all the currents generated by a dynamo shall be made to flow in one direction in the external circuit, the process being known as 'commutation,' and the part of the machine by which the alteration is effected is termed the 'commutator.' Directly this has been successfully performed, the dynamo is capable of a new and important development, for it is then possible to use all or a part of the current which is generated in the armature, for the purpose of magnetising the field-magnets. The smaller auxiliary machine, which, in most of the dynamos previously described, has been employed to excite the field-magnets, can therefore be dispensed with, and the machine made 'self-exciting.'

We come then to the consideration of the means to be employed in order that the currents which are generated in alternate directions can be commutated so as to flow in one direction *in the external circuit.* Referring again to fig. 120, we remember that the *direction* of the current is unaltered (although it varies in E.M.F., and therefore also in strength) during the first half-revolution of the rectangle, and that, at the end of that half-revolution, the reversal in direction takes place. Now, a moment's reflection will show that if, just at the end of this first half-revolution, the positions of the two brushes on their respective rings were interchanged, the current generated during the second half of the revolution would flow in the same direction round the external circuit as the preceding current did, because, although really generated in the reverse direction, it is entering the external circuit at the other end. This is the fundamental principle of commutation; only, instead of shifting the brushes, the change is effected at the right moment by a modification of the ring or rings against which they press.

The simplest possible form of commutator is shown in section in fig. 143 Instead of two brass rings, a single brass ring or tube is employed, but with the difference that it is split lengthways into two halves or segments, *a b*, insulated one from the other. Each end of the coil of wire is connected to one of these segments, and the brusnes or flat springs are so situated that they press upon the divisions between the segments at the moment that the coil is in the vertical position—that is to say, in the position where the reversal of the current takes place. Just at that moment, then, the ends of the coil in contact with the respective brushes are also reversed, and the result is that when the coil is rotated uniformly, a succession of short currents passes through the external circuit, each current rising and falling similarly, but all impelled through the external circuit in the same direction.

FIG. 143.

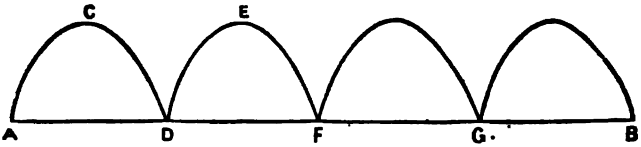


The length of the wire can easily be increased by winding it in a number of convolutions, instead of in a single rectangle, when, as a matter of course, the E.M.F. will be increased proportionately.

The variation in the E.M.F. developed by an ideal alternating-current dynamo is shown in fig. 120, where the line A B represents the normal or zero potential, the curves above it indicating the gradual rise and fall of, say, the positive potential, and those below it the opposite, or negative potential.

Fig. 144 exhibits, in a simple manner, the result of replacing the two metal rings by a split tube, or simple two-part commutator. A B again indicates the zero potential, and the curve A C D the varying potential developed during the first half-revolution; but, instead of the second half developing in the external circuit a negative potential, it is commutated into an external positive one, so that a series of currents, each of brief duration, is urged

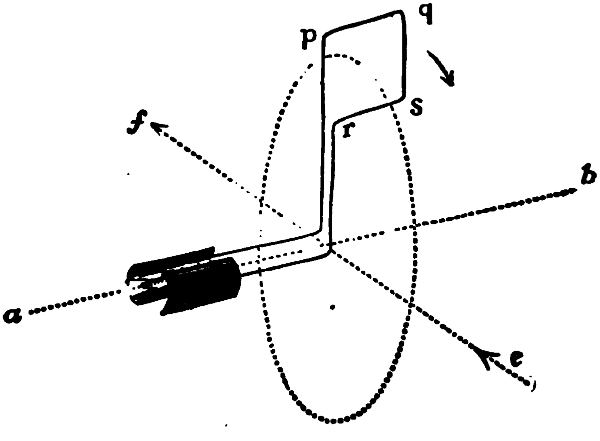
FIG. 144.



through the external circuit in one common direction. The total amount of current generated is, however, the same as before, although its strength oscillates rapidly between zero and the maximum.

A current varying so much in strength is, however, of almost as little service for many purposes as alternating currents, for, in most cases, the current must not only be uniform in direction,

FIG. 145.

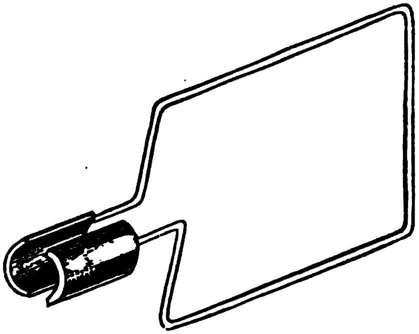


but constant in strength. The methods by which an almost steady current can be obtained will be understood more easily when studied in connection with an armature constructed of coils wound on a somewhat different system. In fig. 145, *a b* indicates the axis of rotation, and *p q r s* a single loop of wire which travels round the circular path indicated by the dotted line. If we suppose the lines of force of the field to be in the direction of *e f*, along, or parallel to, a diameter of this circular path, then they will be cut by the coil in a manner somewhat similar to that of the rectangular coil which we have just been considering.

The movement from the vertical position through the first half-revolution produces a current which rises to a maximum when the coil has turned through an angle of 90°, and falls to zero again when the coil reaches 180°, while the current generated in the next half-revolution is exactly equal in strength, at corresponding positions, though opposite in direction; but it can be commutated in precisely the same way as in the case of the rectangular coil. The ends of the coil are connected to the metallic segments (equivalent to *a b* in fig. 143) of a simple two-part commutator.

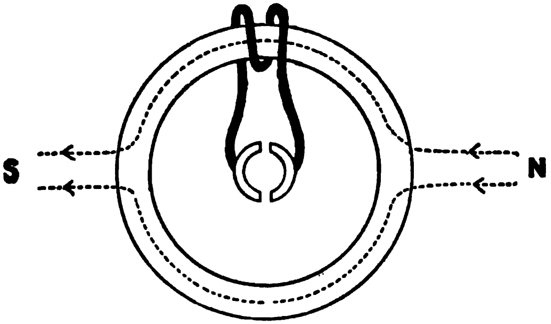
There is, however, one great difference between the two methods. No portion of the coil shown in fig. 146 acts prejudicially, although the portions connecting the horizontal limbs are always idle, inasmuch as they do not cut, but only slide, through the lines of force. But with the coil shown in fig. 145 the case is different. There are still two idle connecting lengths, *p r* and *q s*, but the E.M.F. induced in the two horizontal limbs *p q* and *r s* is in the same direction in each—say from *p* to *q* and from *r* to *s*—because they always cut the lines in a similar sense, although at different rates; they therefore act in opposition to each other. But the outer limb *p q* traverses a greater portion of the field and moves at a greater linear velocity than does *r s*, and consequently, as it cuts more lines of force, and at a greater speed, than *r s*, the E.M.F. generated by it is the greater, the resulting current round the coil being therefore that due to the preponderance of the E.M.F.

FIG. 146



of the limb pq over that of rs. Now, the lines of force which the outer limb cuts in excess of those cut by the inner limb are simply those which pass through the coil when it is in the zero position, as in fig. 145, and it is evident that if the field is uniform and the coil comparatively small the lines thus embraced will be very few indeed, and the use of iron to increase their number immediately suggests itself. It is most advantageous to make the iron in the form of a ring, as shown in fig. 147, and cause it to rotate with the coil.

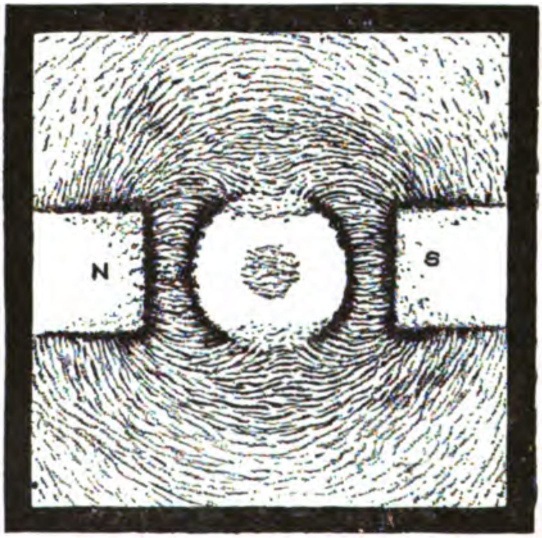
FIG. 147.



In fig. 148 is illustrated the effect of placing a ring of iron in a magnetic field. The apparatus employed to obtain this figure consisted of a quantity of thin soft iron wire wound into a ring, and placed between the opposite poles of two powerful bar magnets, a sheet of paper being laid over them, and iron filings sprinkled upon it. The spaces free from filings represent those places where the permeability of the iron is sufficiently high to prevent any appreciable number of lines of force extending above the paper so as to give direction to the filings. The manner in which the lines converge into the ring should be noted, and it will also be observed that at two places, on a diameter at right angles with the lines, the magnetic effect above the paper is considerable. The reason for this is that the greatest number of lines pass through the iron at these points, and the permeability is sufficiently reduced to allow some lines to leak above the paper. Comparatively few lines pass diametrically across the ring, about half of them going through the upper and half through the lower part of it, and therefore the inner limb of the coil (fig. 147) cuts but very few lines, and the resulting E.M.F. is practically that developed by the outer limb alone.

In the case illustrated in fig. 147 only one-half of the total number of lines of force urged through the iron can, at any one time, pass through the coil, and some device is therefore necessary to enable the other half to be utilised. Now, since the induced E.M.F. is the same in any given position after the coil has passed 180° as it was in the corresponding position after it had passed the zero point, it is clear that a second coil might with advantage be placed at the opposite extremity of a diameter of the circular path described by the coil. We will assume that the limbs on the outer periphery alone are active, and it will be seen that if the induced current flows from front to back in the outer limb of the upper coil, it will flow from back to front in the outer limb of the lower coil, because these limbs always cut the lines from opposite

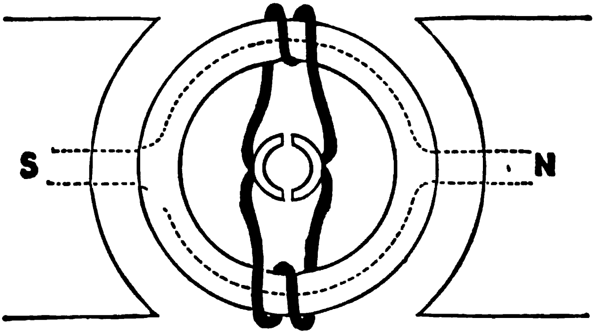
FIG. 148.



sides, *viz.* one from above and the other from below. The E.M.F. is, however, at any moment equal in each, and, by joining the ends which are at a positive potential to one segment and the ends which are at a negative potential to the other segment, both coils are made to deliver their currents in the same direction to the external circuit.

Fig. 149 illustrates the arrangement for employing two such coils; they are similarly wound (right-handedly in this case), and their *adjacent* ends are joined to the same section of the commutator. Now, as they are at opposite extremities of a diameter, they pass at every moment through parts of the field where they act with equal effect, and therefore, as already pointed out, the E.M.F. will be the same at the extremities of each coil. Since the ends of the two coils, which are at the same E.M.F., are joined to the same segment of the commutator, the E.M.F. due to both coils is only the same as that produced by one of them. It is, in fact, an exactly analogous case to that of joining two primary cells of equal E.M.F., in parallel. There is also the similar advantage here that because the coils are joined in parallel the internal resistance between the two segments is only half that of one coil, and, as we have seen, any arrangement that so reduces the internal resistance of a current generator is sometimes very valuable. By increasing the number of turns in the coils we increase the E.M.F., because a greater number of conductors in series, round the peri-

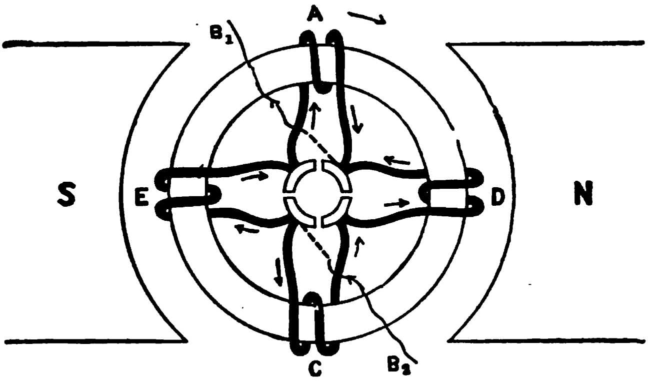
Fig 149.



phery, are usefully cutting lines of force; but, of course, the number must be exactly the same in each coil. In figs. 147 and 149 there are two active conductors to each coil.

We are now in a position to proceed with the consideration of a method for making the short fluctuating currents depicted in fig. 144 approach more nearly to a continuous steady current. These short currents are at a minimum when the coils are at right angles to the lines of force, or at that point where the reversal of the induced current takes place, and it is evident that if a second pair of coils be placed at right angles to this existing pair, as in fig. 150, they will always lie parallel to the lines of force, or be in

FIG. 150.

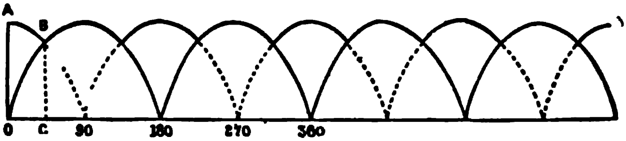


the position of best action, just at the moment when the first pair are almost idle. But it now becomes necessary to divide the commutator into four parts, all the coils being, of course, similarly wound, and the adjacent ends of adjacent pairs connected to the same segment of the commutator. When only two segments are employed, the brushes, as we have observed, are placed so that the divisions of the commutator pass them just at the moment when the coils are at right angles to the lines of force, and when they are almost idle. In the present case, with four coils, the brushes must also be placed so that the division between each pair of segments on the commutator passes a brush when the coil connected to that pair of segments is in the position of least activity, viz. with its plane at right angles to the lines of force. We shall see presently that there are several causes which combine to slightly vary this particular position, although it can always be found.

In fig. 150 the brushes are indicated by dotted lines, and are shown slightly out of what we have hitherto considered to be their correct position. Supposing the lines of force to pass straight across from one pole-piece to the other, the currents in the various coils would be in the direction indicated by the arrows, and the resulting current could be led from the armature to the external circuit by the upper brush B_1, entering the armature again by the lower brush B_2. The two horizontal coils D and E are in the position of greatest activity, while the vertical coils A and C are almost idle, and merely serve to conduct the current generated by the active coils to that segment of the commutator which the brush is touching. A moment later A and C will each begin to generate a current in the opposite direction to the one now flowing in them, but as by that time they will have passed the brushes, their opposite ends will be in contact with the same brushes, and the direction of the current in the external circuit will remain unaltered. When the plane of each coil makes an angle of 45° with the lines of force, they are equally active, and the E.M.F. at the brushes is twice that which is at that moment being developed by one coil.

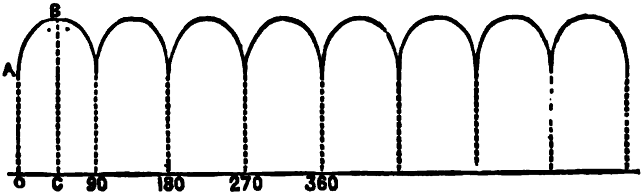
The resulting E.M.F., due to the joint effect of the double instead of the single pair of coils, is still far from constant, and, as before, we must determine at what positions of the coils the E.M.F. is at a maximum and where it becomes a minimum. The curve (fig. 144) illustrates the variation of the E.M.F. due to one coil or one pair of coils, and as, when this E.M.F. is highest, that of the second pair of coils is lowest, and *vice versâ*, the relative magnitude of the E.M.F. generated by two pairs of coils at different positions may be indicated by the overlapping curves in fig. 151. From this we wish to construct a curve which shall show how the E.M.F. *at the brushes* due to the effect of both pairs of coils varies. Now, twice during each revolution one of the two pairs is for the moment acting alone, and, consequently, the E.M.F. at the brushes is simply that due to this pair, and is proportional to the length of the perpendicular line O A. At this moment the E.M.F. at the brushes is at its lowest value, and the length of this line O A determines the lowest point on the curve which we desire to construct. Immediately after this point is passed both pairs are acting together, the activity of one increasing and that of the other

FIG. 151.



decreasing. At a certain stage they will be acting with exactly equal effect, and this stage is indicated by the intersection in B of the two curves; it occurs when each coil makes an angle of 45° with the lines of force. To obtain, therefore, the resulting E.M.F. at the brushes, we must add together these two equal E.M.F.'s; consequently, twice the length of the line C B must be taken as the height of this the highest point in the new curve. When the coils have rotated through another 45°, one pair is again idle and the other at its maximum activity, so that we again reach the lowest point of the curve. The curve so constructed is shown in fig. 152, and indicates the manner in which the total

FIG. 152.

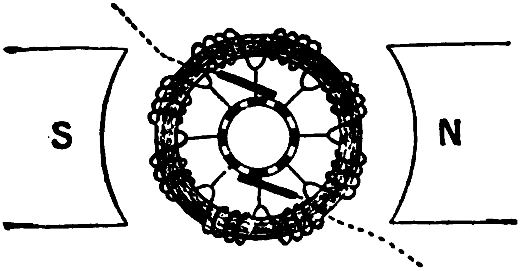


E.M.F. at the commutator brushes fluctuates when the armature consists of two pairs of coils arranged as in fig. 150. The resulting current will also fluctuate similarly, depending in strength upon the gross resistance in the circuit.

A little reflection will make it obvious that the variation in the E.M.F. can be further diminished by the employment of a yet greater number of pairs of coils in the armature, providing that they are placed so that they each come into the position of best action at the moment when the resulting E.M.F., without their individual aid, would be at a minimum.

For instance, a coil might be placed exactly midway between each of those wound on the armature shown in fig. 150; that armature would then consist of eight coils in four pairs, and the commutator of eight bars or segments (fig. 153) The current from such an armature would be far more steady than one from the four-coil armature; in fact, it may be stated generally that the greater the number of coils composing the armature, the less the fluctuation of the current. Of course there is a practical limit to the number of coils; for instance, the commutator with this kind of armature must have as many segments as the armature has single coils, and its construction and the making of the necessary connections would be difficult and expensive if the number were excessively increased.

FIG. 153



It will be observed that in fig. 153 the whole armature conductor is wound continuously round the core; it is divided into sections having four convolutions each, and a connecting wire is led from the junction of every two adjacent sections to the proper segment of the commutator. The result is of course the same as if the ends of each section were brought direct to the commutator segment, while the actual length of the armature conductor, and therefore the resistance, is slightly reduced. The black portions of the circle represent the metallic segments, the white spaces between them indicating the insulating material.

In order to increase the E.M.F. developed in a given field at a given speed, we must increase the number of conductors on the outer periphery of the armature, which can be done by adding to the number of convolutions, although this also increases the internal resistance. In the armature illustrated there are thirty-two active portions of the wire round the whole external periphery, but as they are joined up in two sets in parallel, the total E.M.F. is only sixteen times that of one active portion.

If we know the number of active conductors joined in series and the number of lines of force which they cut per second, it is easy to calculate the resulting E.M.F. The E.M.F. developed by any particular conductor moving circularly in a uniform field varies with its position, and is, as we have seen (Chapter VIII.), proportional to the cosine of the angle which the plane of the coil of which it forms a part makes with the lines of force; or to the sine of the angle through which the coil has turned from its position at right angles to the lines of force. But we need not now trouble ourselves with this consideration, for, in a symmetrically constructed armature of many convolutions, the place of each conductor as it moves to a position of greater or less activity is immediately filled by another, and the total E.M.F. remains unaltered. Since each active length undergoes precisely the same inductive effects, the average E.M.F. induced in each is the same, and the total E.M.F. will be equal to the number of active conductors round one-half of the armature multiplied by the average E.M.F. developed by one of them during half a revolution.

Supposing the armature to consist of forty-eight convolutions and the E.M.F. developed by one of the active limbs to be 2 volts, then the whole E.M.F. would be $2 \times 24 = 48$ volts.

The average E.M.F. developed by each active conductor depends upon the speed at which it moves, and the number of lines cut by it; in fact, we have seen that if a wire, one centimetre long, is moved at a velocity of one centimetre per second transversely through a field of unit strength (that is, a field having one line of force per square centimetre), then the resulting E.M.F. will be equal to one C.G.S. unit. This unit being so very small, the volt is taken for practical use, having a value 10^8 or 100,000,000 times that of the C.G.S. unit. So that after calculating E.M.F. in C.G.S. units, the result must be divided by 10^8 to obtain the E.M.F. in volts.

It is preferable to know the number of lines cut per second, and then we need not know the length of the conductor or the strength of the field in C.G.S. units, nor need the field be uniform. Referring again to fig. 153, suppose there are 16,000 lines of force forced through the armature core, these lines will all be cut twice by each conductor during one complete revolution. If the armature makes one revolution per second, each conductor will cut 32,000 lines per second and generate an average electro-motive force of 32,000 C.G.S. units. And as there are sixteen conductors in series, the total average E.M.F. as measured at the brushes will be 16 × 32,000 = 512,000 C.G.S. units, or

$$\frac{512{,}000}{10^8} = \cdot 005 \text{ volt nearly.}$$

If the armature made ten revolutions per second, the E.M.F. would be ten times greater (i.e. 0·05 volt), because each conductor would now cut ten times the number of lines per second.

In fact we may say that the average E.M.F. generated in an armature of this description is equal to

$$N \times \frac{P}{2} \times 2n, \text{ that is, } NPn \text{ C.G.S. units,}$$

or

$$\text{average } E = \frac{NPn}{10^8} \text{ volts,}$$

where N is the total number of lines of force urged through the armature core; P the total number of active conductors lying round the periphery, and $\frac{P}{2}$, therefore, the number in series; n the number of revolutions per second, and $2n$, therefore, the number of times per second which the whole of the lines are cut by each conductor.

The E.M.F. obtained in the last example (0·05 volt) is very low, because we assumed a rather low speed and few lines of force. In practice it is not unusual to force several millions of lines through the armature core. Supposing the number to be 3,000,000, and the number of conductors round the periphery to be 150, then if the armature is driven at 1,200 revolutions per minute, or 20 per second, the E.M.F. developed would be

$$\frac{3{,}000{,}000 \times 150 \times 20}{100{,}000{,}000} = 90 \text{ volts.}$$

The above is a fair example of what obtains in actual practice, and the student will readily perceive that it is necessary for the quantity of iron in the armature core to be considerable, otherwise with such a large number of lines of force the magnetic induction through it (that is, the number of lines per square centimetre) would be abnormally high. We know that the permeability of iron decreases rapidly when the induction through it exceeds a certain amount, and then a large number of the lines leak diametrically across the ring instead of taking the path indicated in fig. 149, many of them passing across the steel driving shaft, the permeability of which may be nearly equal to that of the 'saturated' iron.

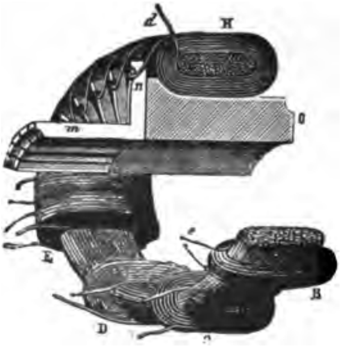
Now, as these lines of force thus leaking across the ring are cut by the inner portions of the conductor (equivalent to *r s* in fig. 145) and act prejudicially, inasmuch as the E.M.F. generated by the inner wires in cutting them is reverse to the main E.M.F., it is evidently inadvisable to endeavour to push the induction too far. As a rule the limit is from 16,000 to 18,000 lines per square centimetre, and if more lines through the core are needed, either the area must be increased or iron of higher permeability employed. The former necessarily entails a greater length of conductor. It is evident that in an armature of the type we are considering, the iron of which the core is made should be of the highest possible permeability, while the quantity of iron or steel used inside the ring should be as small as possible to minimise the tendency to cross-leakage. This latter consideration implies that iron should not be employed for the purpose of mechanically connecting the ring to the shaft. In practice, gun-metal or some other non-magnetic alloy is used.

The first armature on this principle was constructed by Pacinotti, but it remained unnoticed until the essential features had been combined in a slightly different form by Gramme.

Fig. 154 illustrates the construction of an early form of Gramme armature, the core being shown cut through, and some of the coils displaced to make it clearer. The core, F, consists of a quantity of iron wire wound continuously to form a ring of the shape shown by the section. Over this is wound about thirty coils of insulated copper wire, B C D, &c., the direction of the winding of each being the same, and their adjacent ends connected together. The commutator segments consist of a corresponding number of brass angle-pieces, *m n*, which are fixed against the wooden boss, *o*, carried on the driving shaft.

The junction of every two adjacent coils is connected to one of the commutator segments, as shown, and two flat brushes of copper wire are pressed against the projecting ends of the segments, and serve to deliver the current to the external circuit. The latest forms of this armature, although identical in principle, are far superior from a mechanical point of view; in fact, the armature here illustrated would fly to pieces if subjected to the stresses which occur in a modern machine.

FIG. 154.



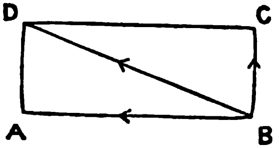
It is necessary that the commutator bars should be firmly held in position, that the wire should be bound or by some means fixed so as to prevent its being shifted, and that the core and with it the coils should be firmly secured to the driving shaft. As far as possible it will be shown, in describing the best types of machines, how well these points are attended to in practice. Especial care must be taken to prevent the generation of eddy currents in the core, and this was the reason why Gramme used rather fine wire instead of a solid ring. We have previously remarked that the E.M.F. which gives rise to these eddy currents is very low (although the current strength may be considerable, because a large mass of metal offers little resistance), and that, therefore, the merest film of insulation between neighbouring wires of the core is sufficient. Except in special cases a coating of shellac varnish, or even a coating of rust, is all that is required, and it should be borne in mind that the space occupied by insulation should always be as small as possible, so as to allow the maximum amount of iron to be used. If the armature is rotated in a simple field between two pole pieces, it is not necessary to subdivide the core to the extent adopted in the earlier Gramme machines, for since the direction of the eddy currents is at right angles to the lines of force and to the direction in which the core moves, there will be no tendency for them to flow in a radial direction, but only along lines parallel to the driving shaft. Therefore the core may be simply laminated, or built up of a number of thin discs of soft iron, thus giving better facilities for mechanical connection with the shaft, and also reducing the magnetic resistance considerably. In entering or leaving the interior of the wire core, the lines of force have to leap across numerous little spaces of low permeability, while in the case of a core built up of discs, not only is the mass of iron greater, but it is also continuous in the direction of the lines, and discontinuous only in the path which would be taken by the eddy currents.

Returning now to a consideration of the phenomena developed by the actual rotation of the armature, we may repeat that the brushes must be so placed that every division between the segments of the commutator passes a brush just at that moment when the coil, the ends of which are connected to those segments, is idle. Now this happens when the plane of the coil is at right angles to the lines of force, so that if the lines of force always retained their regular straight direction between the poles of the field magnet, it would be easy to fix the correct position for the brushes. But, unfortunately, the field is considerably distorted immediately the armature is caused to rotate and the current established. This distortion is due to the fact that the armature itself becomes a powerful electro-magnet, having lines of force which are not coincident with those of the field magnets.

The two halves of the core are, as a matter of fact, magnetised by the currents passing round them, and in such a manner that their similar poles are adjacent to each other and situated at the points where the two currents enter and leave the external circuit. Now, if two semicircular magnets of equal strength are placed so as to form a circle with their *unlike* poles adjacent, they form a complete closed magnetic circuit, nearly all the lines of force taking the path of the iron or steel, and there is consequently very little external magnetic effect observable. But if these same semicircular magnets are placed with their *like* poles adjacent, there is abundant external evidence of the magnetic strength of the combination. The circle acts, indeed, as if it were a single magnet, the distance between its poles being the length of the diameter. Some of the lines of force find their way back across the diameter to the opposite pole, while others pass round outside the circle, a much larger proportion taking this course when, as in the case of the dynamo, there are large masses of iron in the vicinity. The position of the brushes determines the position of the poles of the armature, and when the brushes are placed on a diameter at right angles to the lines of force of the field, these poles are also at right angles to those lines of force.

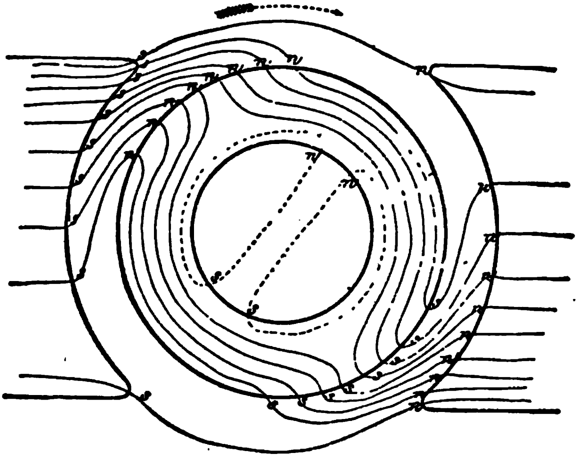
It is manifest that as the tendency is for the armature to generate a magnetic field in one direction, while the field magnets strive to maintain one in another, the direction of the resultant field must lie between the two, the exact position depending to a great extent upon the relative magnetising forces of the armature and field magnets. Were these relative forces known, the direction of the field might be determined approximately by the well-known 'parallelogram of forces' (see fig. 155). In this case the line A B represents by its position the direction, and by its length the magnitude of the magnetising force due to the field magnets alone, while the line B C, drawn at right angles to A B, represents the direction and force of the field due to the armature. Then the diagonal B D of the completed parallelogram represents both in magnitude and direction the resulting magnetic field. Now the brushes must be set on a diameter at right angles to these resulting lines of force. Hence this shifting of the field due to the reaction of the armature necessitates also the shifting of the brushes through a corresponding angle, equal, in fact, to the angle D B A.

Fig. 155.



This altered position of the brushes is commonly known as the *lead* given to them, and the angle through which they are moved is known as the angle of lead. In every dynamo the lead is forward, or in the direction of the rotation of the armature. But the parallelogram of forces referred to above does not exactly indicate the true angle, because immediately a lead is given to the brushes, the polarity of the armature is shifted through a corresponding angle, the result being to still further distort the field and again increase the angle of lead. It will be evident that if we wish to reduce the angle D B A (fig. 155) it can be done by decreasing B C or increasing A B, which in either case would result from making the magnetising force of the field magnets great as compared with that of the armature. Practice also dictates, for this and for other reasons, that the magnetic field in which the armature revolves should be as strong as possible, and always very much stronger than that developed by the armature itself. In fig. 156 is illustrated the direction of the resultant field of a dynamo when the armature is revolving in the direction indicated by the arrow, and is generating a current. It will be observed that the lines of force *n s*, *n s* are considerably distorted or dragged out of their normal position, and that this distortion takes place in the direction of rotation. The lines which cross the space inside the armature ring indicate the direc tion of leakage, corresponding to that illustrated in fig. 148.

FIG. 156.



When the external resistance through which a dynamo is working is varied, the current in the armature, and therefore the field produced by it, also varies ; the same cause may also alter the field produced by the field magnets if the machine is 'self-exciting,' and consequently in practice the angle of lead sometimes varies considerably. If the effective fields produced by the field-magnets and the armature were varied in the same proportion, the angle of lead would remain constant ; but we shall see presently that because the induction through and the permeability of the field-magnet and armature cores do not vary together, as well as for other reasons, this proportion is not maintained, although the currents producing those fields may be equally increased or diminished. Too much stress cannot be laid upon the necessity for setting the brushes in the proper position, and to facilitate matters they are usually mounted on an insulating rocker so that they may be shifted together through a considerable angle until the correct position is found. When the field is a simple one, such as that between the two poles of a magnet, and providing it is also uniform, the brushes are placed at opposite extremities of a diameter of the commutator.

When the brushes are not properly adjusted, the coils are short-circuited while they are more or less active, and considerable sparking occurs at the commutator, injuring that important part of the machine, and giving evidence of wasted energy.

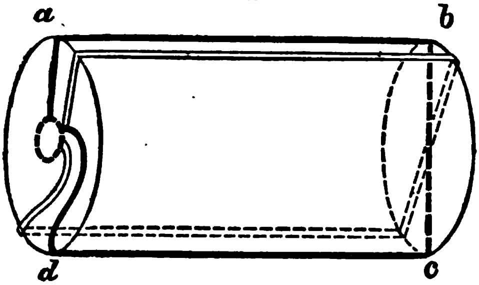
Practically the best position of the brushes can be found by shifting them while the machine is running (the external circuit being at the time completed) until there is very little or no sparking observable ; and it is found that they must be set even a little further ahead than the point where they are at right angles to the direction of the resultant lines of force. This slight extra lead is necessitated by the rather peculiar and important action which takes place in a coil as it passes a brush. The brush has a sufficiently wide bearing on the commutator to bridge over the interval between the two segments and so to short-circuit the coil attached to them for a brief interval of time ; and although this may take place when the coil is in itself, as a generating coil, almost inactive, it must be remembered that it has considerable self-induction, consisting as it does of a number of convolutions of wire wrapped round a comparatively large mass of soft iron. We have considered at length the reasons which prevent a current being suddenly started or stopped in any circuit which has an appreciable amount of self-induction, from which it is evident that although the coil itself may not be actually generating any current, yet it is carrying the whole of the current generated by the other coils in the same half of the ring, and when short-circuited by the brush this current will not immediately die out, but will become even stronger for a moment and then expire. Independently of this it is impossible in practice to absolutely attain the theoretical condition of each coil being idle even for the briefest possible interval during which the coil might be short-circuited; and although the E.M.F. generated when the coil is least active may be very small, yet its resistance is as a rule so extremely low, being but a small fraction of an ohm, that the current strength becomes perforce considerable. The energy of currents so circulating round the coils while they are in turn short-circuited, is expended in heating the wire, which heat represents so much energy lost to the external circuit where it might have been usefully employed, and this effect must be remembered as one of the many causes which necessitate special attention being paid to *ventilation* in designing a dynamo armature. To ensure the entire stoppage of the current, and also even to allow sufficient time for a current in the opposite direction to be just started in the coil before it is actually thrown into circuit again in the other half of the armature, it is advantageous to have the brushes rather thick and to give them the slight extra lead above referred to.

But much can be done to reduce the angle of lead and minimise sparking by making the field very strong and constructing the armature with many sections, each of few convolutions. In some modern machines each section consists of but one convolution, and absolutely no sparking can be observed, while, the field-magnets being very powerful, the angle of lead is very small.

It will be remembered that we commenced the study of the direct-current dynamo with the aid of a simple rectangular coil (fig. 146), but that subsequently, to make the development of the subject easier, a different system of winding was introduced, leading up to the Gramme armature. We are now in a position to comprehend more readily the manner in which excellent armatures, commonly known as 'drum' armatures, are constructed upon the principle of the rectangular coil first mentioned. The earliest drum armature was devised by Von Hefner Alteneck, and was really a natural development of the shuttle armature so much used in small magneto machines. This shuttle armature, consisting, as it does, of one coil of many turns, gives a current fluctuating from maximum to zero twice in each revolution, and greater steadiness was aimed at and obtained by placing a number of coils symmetrically round the core; in just the same way that a considerable number of coils wound on the Gramme principle yields a more nearly constant current than would result from a single coil. A drum armature is somewhat more difficult to construct and to illustrate, and although the fundamental principle is in all cases that just indicated, there are many ways of making the necessary connections, some of which will be described when dealing with actual machines.

The general principle may be gathered from fig. 157, where only two adjacent sections are shown, each having one turn. The core is shaped like a cylinder, or drum; a commutator, similar to those already described, being placed at one end in a line with its axis. From one segment the first coil ascends up the face of the drum to *a*, thence lengthways along the cylinder to *b*, whence it passes across a diameter to *c*, and along the length of the cylinder to *d*. From *d* it is brought round the face and connected to the segment next to that one to which the other end of the coil is joined. The second coil, shown by open lines for distinction, starts from the segment at which the first coil terminates, and is wound similarly to that coil, being placed a little further round the drum as shown. Its two ends are connected to adjacent segments, and, in a similar manner, coils would be placed all round

FIG. 157.



the cylinder, equidistant, and with the ends of each joined to two adjacent commutator segments, so that each segment has two wires connected to it. Many of the best drum armatures are constructed with but one convolution in each section, but when it is desired to increase this number the wire is simply wound the requisite number of times round the cylinder, and the end of the last convolution led from the point *d* to the commutator segment. Of course, the wires cannot be brought diametrically across the faces, as shown at *b c*, on account of the driving-shaft, and when there are several convolutions in each section care is taken to place an equal number of the wires on either side of the shaft, so as to preserve a mechanical as well as an electrical balance. In any case, great care has to be taken with these cross-connections, which are, in fact, a serious source of trouble, for, since portions of all the coils overlap here, it is possible to get wires having a high potential difference very close together. This difficulty does not arise with a Gramme ring.

The great advantage peculiar to a drum armature is the fact that the conductors usefully cut *all* the lines of force passing through the armature core. The only idle wire is that used for connection across the faces or ends of the cylinder; and no part of the conductor can generate an E.M.F. in the counter direction. Consequently, iron may be employed for all the internal fittings; in fact, but for the necessity for allowing space for ventilation, the whole of the inside of the armature might be occupied by iron. Since the active limbs, *a b*, *c d*, always cut the lines of the field from opposite sides—viz. one from above, the other from below—the current is induced, from front to back in one and from back to front in the other, so that it circulates in the same direction round the coil.

Each coil is equivalent, then, to two diametrically opposite coils in a Gramme armature, and there will be the same number of commutator segments as there are coils. The reversal of the current, of course, takes place as each coil passes the zero position—viz. with its plane at right angles to the lines of force—and it is in this position that the segments to which it is connected pass the brush. Also, as in the case of the Gramme ring, the resistance from brush to brush, through two halves of the armature in parallel, is only one quarter of that of the whole armature in series, and in calculating E.M.F., the formula, $E = \frac{N P n}{10^8}$, holds good, P being the number of active conductors, such as *a b*, round the periphery of the drum.

The drum armature is far more efficient than any other form, and we may briefly compare the relative advantages of the drum and ring type by supposing that we have two armatures of equal diameter, and having conductors arranged round them equal in number and length. The magnetic resistance offered by the drum armature will be the smaller, because the quantity of iron in its core is greater, and therefore a given 'magneto-motive force' can urge more lines of force through it than through the ring armature.

Further, the whole of the lines passing through the drum armature are usefully cut by the conductors, while, in the case of the ring, some leak across to the shaft and are cut by the inner portions of the wire in such a manner as to reduce the main E.M.F. Therefore, with a given magneto-motive force to maintain the field, the drum armature will give a much higher E.M.F. than the ring when they are driven at equal speeds. Equal E.M.F.'s might be obtained by reducing N, the number of lines of force, or P, the number of active conductors; but the factor which it is usually sought to keep as low as possible is *n*, the number of revolutions per second. One great practical advantage of a drum armature is that it enables slow-speed machines of comparatively moderate proportions to be constructed, and it will be observed that few slow-speed dynamos have ring armatures; indeed, the drum patent having recently lapsed, very few simple ring armatures are now used in any but small machines. Since the proportion of idle wire is slightly less in the drum than in the ring type, its conductor resistance is rather lower, while, on the other hand, it has the disadvantages that it is difficult to make it as strong mechanically as the ring, the cross-connections are somewhat troublesome, and, as a rule, special arrangements are needed to ensure sufficient ventilation.

Having discussed some of the theoretical points involved in the construction and action of direct-current dynamo armatures, we will now consider the methods of maintaining the field, which, it will be remembered, must be as strong as possible. As in the case of the more powerful of the machines described in the preceding chapter, electro-magnets (called the field-magnets) are employed for this purpose, and great care should be exercised in their design. Practical difficulties and economy in construction somewhat influence the shape, but in every case the great object should be borne in mind, viz. the necessity for leading as many lines of force as possible through the space between the poles, in which the armature is made to revolve.

The actual magnetising force, consisting of a current passing through a coil of wire, is proportional to the amperes of current flowing and the number of turns of wire in the coil, and, as has already been fully explained (Chapter VII.), the quantity represented by the product of these two factors is referred to as the 'ampere-turns.'

Now, for any given machine, the number of lines of force which must be urged through the armature is usually determined beforehand, but as with every electro-magnet, of whatever design, there is a certain amount of 'leakage,' only a portion of the lines generated by the ampere-turns pass through the armature.

But power is expended in the generation and maintenance of the lines of force, and those which are rendered useless by leakage represent so much power wasted. It is obviously imperative that this waste should be reduced to a minimum, and the greatest possible proportion of the lines developed led through the armature. This may be accomplished by making the magnetic resistance of their path very low. The whole magnetic circuit should, preferably, approximate to the circular form, and whether good soft iron or cast-iron is employed, its sectional area must be sufficient to prevent the saturation point being readily reached.

The spaces between the pole-pieces of the field-magnet and the core of the armature offer considerable magnetic resistance, which may roughly be taken as nearly proportional to the distance between the iron surfaces, the permeability of the copper wire and its insulation being about the same as that of air. The only way of overcoming this serious difficulty is to reduce the distance between the iron surfaces as much as safety will permit, and, since this minimum distance is nearly the same in machines of all sizes, we see one reason to account for the observed fact that small dynamos are less efficient than larger ones.

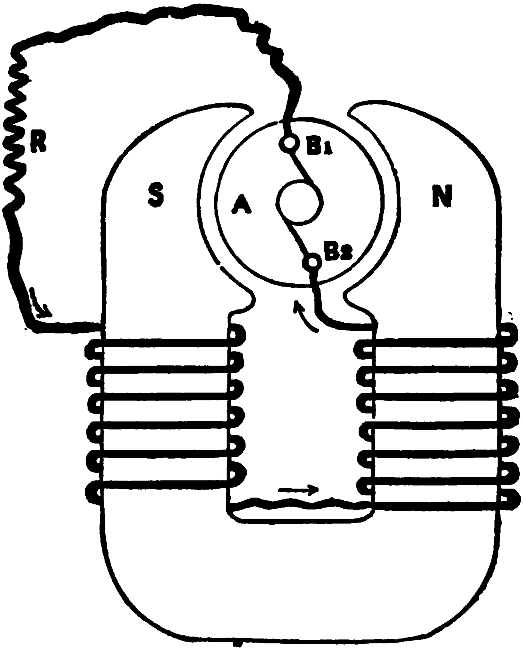
It must not be forgotten that while the permeability of iron decreases with an increase of the magnetic induction through it, that of air remains constant, and the difference between the permeability of the nearly-saturated iron of the field-magnets, and that of the air space, is never anything like the difference usually given for unsaturated soft iron and air.

Two very important considerations influencing the construction of field-magnets are economy and mechanical strength, and in practice, as we shall see, it is often considered advisable where the weight is unimportant to use cast-iron for part or all of the field-magnet core. It is preferable to forge or cast the core in one piece, as joints break the molecular continuity and increase the magnetic resistance considerably; this disadvantage is minimised by making the surfaces in contact fit truly. The principal practical objection to the use of cast-iron is that, since its sectional area must be at least twice that of wrought-iron, a much greater amount of copper is required to form the field-magnet coils. Copper, even now, is expensive, while cast-iron cores are far less costly than equivalent ones of wrought-iron, and the student should observe how different makers aim at true economy in this matter. Even leaving out the question of cost and weight, it does not by any means follow (as is sometimes supposed) that a dynamo properly designed to perform certain work, and having cast-iron in its construction, is inferior to one built wholly of wrought-iron to perform the same work.

The composition of the 'ampere-turns'—that is, the proportion of current strength to the number of convolutions—will depend largely upon the manner in which the exciting current is obtained; for it is sometimes necessary to have considerable resistance in the coils, and then the number of convolutions may be made great and the current correspondingly weak; while in other cases a high resistance is inadmissible, when only a few turns can be employed, and the necessary magneto-motive force must then be obtained by the aid of a heavy current.

At the beginning of this chapter we referred to a very important benefit following the commutation of the current, viz. the possibility of using all or part of the current generated in the armature for the purpose of magnetising the field-magnets, and the simplest method of doing this, in which the whole of the current is so employed, is exemplified in fig. 158. A machine having its connections made in the manner there shown is known as a 'Series Dynamo.'

FIG. 158.



S N are the pole-pieces of a massive horse-shoe electro-magnet; the armature A revolves in the space between them, B_1 B_2 being the brushes which press against the commutator, and by means of which the current generated in the armature can be led to any desired point. In this case, one end of the wire forming the coil of the electro-magnet is connected directly to the brush B_2, the other end being joined through the external circuit R to the opposite brush B_1, so that the circuit of the field-magnet is completed through the armature coils. Hence the whole of the current generated in the armature must pass round the coils and magnetise the electro-magnet. But how is the current to be started in the first instance? It so happens that even the purest soft iron is found to retain some of the magnetism imparted to it, therefore the cores of a dynamo always retain an appreciable amount.

This 'residual' magnetism is sufficient to project a few lines of force through the armature coils; so that, when the armature is rotated, a feeble current is generated in them. The connections being made as in fig. 158, this current leaves the armature by the top brush B_1, flows through the external circuit, and, returning to the machine, passes round the coils of the field-magnets, the circuit being completed through the lower brush B_2. The feeble current sent in this way through the field-magnets increases the strength of the field in which the armature rotates, and, consequently, the current generated also becomes stronger. This further increases the magnetic field developed, and, consequently, also the current strength, action and reaction succeeding one another, until presently the current becomes very strong indeed. This increase does not, however, continue indefinitely, there being two especially important restrictions which tend to fix a limit to the current produced. In the first place, although the core of the field-magnet may be very massive, its magnetisation eventually approaches the saturation-point, beyond which an increase of the current in the coils would not by any means involve a corresponding increase in the strength of the effective field. Secondly, the rotation of the armature, although performed with little effort at the commencement, requires a considerable expenditure of energy as the strength of the current increases. We are even able to estimate the relative amounts of the power required to turn the armature while currents of different strengths are being generated. For our present purpose the calculation can be made very simple by ignoring the power lost in mechanical friction, &c. The electrical power which is being developed in any circuit can be found by simply multiplying together the electro-motive force in volts and the current strength in amperes in that circuit, the result being the number of watts of power developed therein, or W = E C, W being the number of watts.

As the E.M.F. is equal to the product of current strength and resistance (that is, E = C R), we may write $W = C R \times C = C^2 R$—that is, the power in watts developed is equal to the resistance in ohms multiplied by the square of the current strength in amperes.

As the resistance of the dynamo armature and magnet coils is always known, only one measurement, that of current strength, need be taken, which can be done by any ammeter of negligibly low resistance.

Supposing, for example, the resistance of the armature to be 3 ohms, and that of the field-magnets to be 2 ohms, then the total resistance is 5 ohms. When a current of 10 amperes is generated without any external resistance, the electrical power appearing in the circuit is equal to $C^2R = 100 \times 5 = 500$ watts, and if the current is increased to 20 amperes, then $C^2R = 400 \times 5 = 2{,}000$ watts.

Now, in both cases at least as much mechanical power is required to turn the armature as appears in the circuit as electrical power. A certain amount in excess is necessary (depending upon the efficiency of the machine), because some energy must be wasted in overcoming the mechanical friction of the bearings, &c., and still more by various electrical causes, such as eddy currents and the currents which flow in the coils during the period of short-circuiting.

The main point, however, upon which we desire at present to lay stress is that the increase in the current is not, and never can be, obtained without a corresponding increase in the power expended in turning the armature; in fact, from the above reasoning it is clear that in a series dynamo such as the one described, the mechanical power expended varies as the *square* of the strength of the current obtained in the external circuit, ignoring the mechanical power lost in the machine during conversion.

The ultimate strength of the current is, then, limited not only by the saturation of the field-magnets, but also by the amount of power at our disposal to drive the armature round. The engine, or other source from which the power is derived, must at least be able to furnish power equal to the maximum electrical power it is desired to obtain, to which must also be added that which is wasted in friction, &c.

With regard to the residual magnetism which is relied upon to start the current, it may be remarked that if the field-magnets are once strongly magnetised by a current passing in the direction in which it is desired the currents shall afterwards be generated, the cores will rarely lose all traces of magnetism, especially if of cast-iron. This sometimes happens, however, when the dynamo is moved, and the magnetism may even be reversed; but matters can easily be righted by passing a current, say, from a few cells for a moment in the proper direction through the field-magnet coils.

Hitherto, the dynamo has been considered as only working on 'short circuit'—that is, with the circuit completed without the introduction of any appreciable external resistance. In practice, we require the current to do a greater or less amount of work in an external circuit, such as developing light in electric lamps or driving an electro-motor. In such a case, part only of the power is expended in overcoming the internal resistance (that is, the resistance of the armature and field-magnets) and maintaining the field, the remainder being employed in the external circuit. It is easy to find the relative amount of power absorbed in the two parts of the circuit. Thus, suppose the strength of the current to be 40 amperes, and the total E.M.F. to be 80 volts, then the total electrical power is $40 \times 80 = 3{,}200$ watts. If, now, the difference of potential between the two extremities of the external circuit is found to be 60 volts, the power absorbed therein is $40 \times 60 = 2{,}400$ watts, for the strength of the current is the same in all parts of the same circuit. The remaining difference of potential is $80 - 60 = 20$ volts, which is the fall along the internal circuit, and which absorbs, therefore, $40 \times 20 = 800$ watts. In this way, the ratio between the power spent in the external and internal portions of the circuit can in every case be measured. The two ends of the external circuit above referred to are called the 'dynamo terminals,' and the potential difference thereat can be measured by any convenient voltmeter. Since, also, the power spent in either portion can be calculated by multiplying the square of the current strength by the resistance of the respective portions of the circuit, and as the current is the same in each, it follows that the energy absorbed in either part is directly proportional to the resistance of that part. Thus, if the resistance of the external circuit is R ohms, and that of the dynamo r ohms, the total resistance is $R+r$. Let the total number of watts developed be W. Then, denoting the watts absorbed in the internal and external parts of the circuit by x and y respectively, we have

$$x : y :: r : R,$$
$$x : W :: r : R+r,$$
$$y : W :: R : R+r.$$

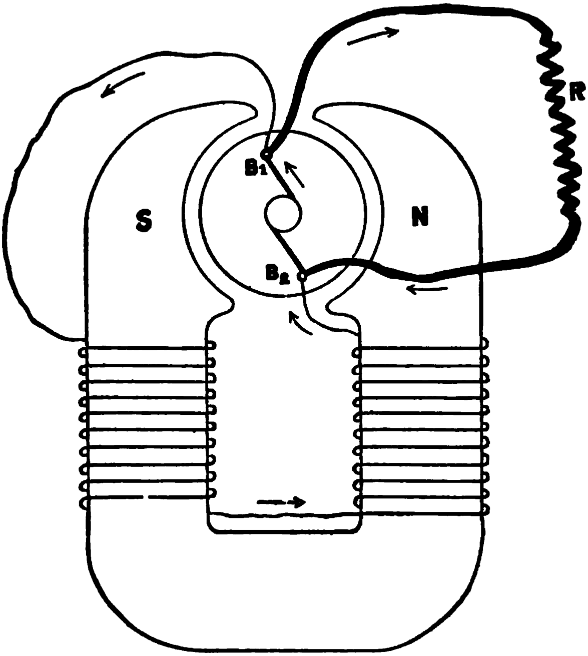
But it is very rarely that any dynamo works through an external circuit of constant resistance; if it is supplying current to electric lamps, some of them are liable to be thrown into or out of circuit at any moment, and the behaviour of a series dynamo under these varying conditions must be briefly noted. Supposing the lamps to be joined up in series, then any addition to the number will increase the external resistance and reduce the current strength, and this means a corresponding decrease in the strength of the field, and, consequently, a further diminution in the current strength If we suppose the lamps to be joined up in parallel, then any addition to the number in circuit decreases the total resistance and increases the current. This, by strengthening the field, still further increases the current strength. So that in either case considerable difficulties arise when a series dynamo is used on a circuit of varying resistance.

Moreover, this variation of the current, while it varies the effective fields of the armature and field-magnet, does not do so in the same proportion. The angle of lead must therefore be altered for every alteration of the current, or injurious sparking at the brushes will ensue.

For these reasons, the conditions under which the simple series dynamo can be conveniently employed are somewhat limited. For general work some method of 'regulation' is essential—that is, some arrangement by which the machine shall be made to develop just as much electrical power as the variations in the external circuit demand from it; the first approximation thereto is obtained by a slight alteration in the manner of winding, giving us what is known as the 'Shunt' dynamo.

In the shunt dynamo the field-magnet coils, instead of being joined up in series with the armature and external circuit, are so connected that they form a 'shunt' *to the external circuit*, and receive, therefore, only a part of the current generated in the armature, the proportion depending upon the relative resistances. Fig. 159 shows the manner in which the connections are made, and the principle, which is very simple, should be readily grasped. The armature is rotated between the pole-pieces, and a certain E.M.F. is set up. The whole of the current generated passes, as a matter of course, through the armature, and we will suppose that its direction in both halves of the armature is upwards, or from the lower to the upper brush. At the upper brush, B_1, the circuit is divided, two paths being open to the current; one round the coils of the field-magnets, by taking which it augments and maintains the

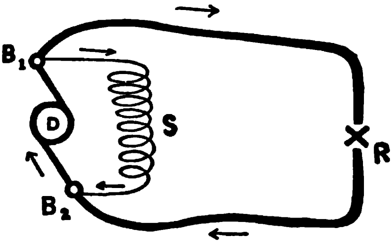
FIG. 159.



field; and the other through the external circuit, where it can be used to run lamps, or perform such other work as may be required. Both of these paths, however, terminate at the lower brush, B_2, and the quantity of the current which goes round either path is, as we have just indicated, simply inversely proportional to its resistance. In case any difficulty should be experienced in understanding the connections or in tracing the path of the current in the various branches, the arrangement is shown even more clearly in fig. 160, R being the external circuit, S the field-magnet coil, B_1, B_2 the brushes, and D the commutator of the dynamo.

The method of measurement applied to the series dynamo can also be adopted with the shunt machine, for the amount of power absorbed in the armature, field-magnet coils, and external circuit respectively, can be found by multiplying the current in that particular part of the circuit by the potential difference at its extremities. The armature resistance must be very low, otherwise, as it carries the whole of the current, the power absorbed therein becomes considerable; on the other hand, the resistance of the field-magnet coils requires to be relatively high. In an actual machine giving excellent results, the resistance of the armature is a trifle less than one-hundredth of an ohm, while the magnet coils offer 16·93$^{\omega}$, or about 1,700 times as great.

FIG. 160.



Supposing this machine were driven at such a speed as to develop an E.M.F. at the brushes of 100 volts, the external resistance R (consisting of a number of lamps in parallel) being half an ohm, then the current in the external circuit would be 200 amperes, and the power usefully employed therein 100 × 200 = 20,000 watts. The resistance of the shunt coils being 16·93$^{\omega}$, and the potential difference at the extremities 100 volts, the current produced therein will be almost 6 amperes. So that 6 × 100 = 600 watts will be absorbed in maintaining the field. The current in the armature of a shunt dynamo is the sum of the two currents in the external branches—viz. the field-magnet coils, and the external circuit, and in this particular case is $6 + 200 = 206$ amperes. The armature resistance is $0{\cdot}01^{\omega}$, and since the fall of potential along it is equal to the product of current strength and resistance, the fall of potential along the armature from brush to brush is $206 \times 0{\cdot}01 = 2{\cdot}06$ volts. Therefore the power absorbed in it is $2{\cdot}06 \times 206 = 424{\cdot}36$ watts, which of course might also be obtained by multiplying together the square of the current passing through the armature by its resistance. Now the whole electrical power developed is 21,024 watts, of which number 1,024 are absorbed in maintaining the field and in overcoming the armature resistance, the remaining 20,000 being usefully expended in the external circuit.

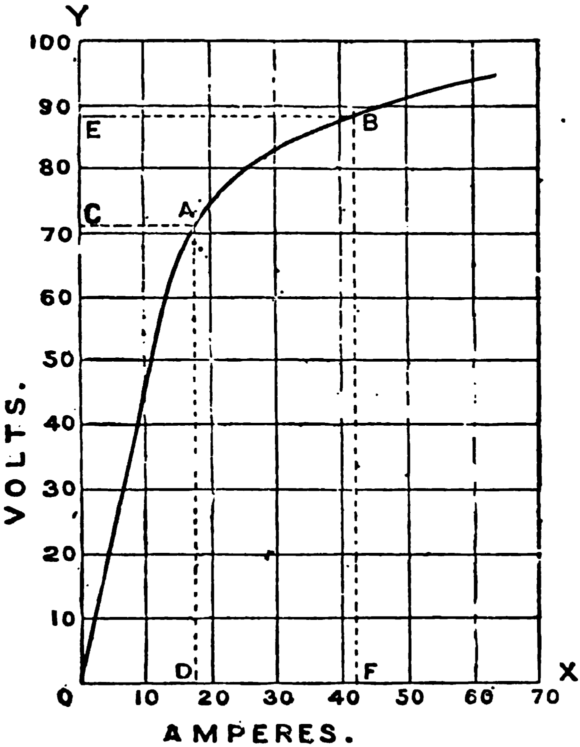
The ratio of the power usefully available to the total power developed is commonly known as the 'electrical efficiency' of the dynamo, and in the case just considered this ratio is $\frac{20,000}{21,024}$, or the electrical efficiency is slightly over 95 per cent. It is hardly necessary to point out that a very slight increase of the armature resistance would considerably lower this figure.

Ignoring for the moment the small amount of residual magnetism, it will be observed that in a series dynamo the field-magnets become demagnetised immediately the external circuit is broken, because the whole of the current is then stopped. In the case of a shunt dynamo, however, if the external circuit R in fig. 160 is broken, there is an alternative path left for the current generated by the armature, viz. round the field-magnet coil S. As the whole of the current will then pass through the field-magnet coil instead of only a portion of it, the strength of the field due to the field-magnet is always at its maximum when the external circuit is disconnected; exactly opposite to the case of the series dynamo. In the latter machine the most powerful current is generated and the field is strongest when its terminals are joined by a piece of thick wire; but this proceeding would have the reverse effect upon a shunt machine, because practically no current would flow round the coils on account of the very low resistance of the alternate path. And, although the shunt dynamo (especially if the resistance of its armature is low) is through a certain range less affected by changes in the external circuit than the series dynamo, neither of them is, for many purposes, sufficiently 'self-regulating,' or able to accommodate itself to these external variations. We may require a dynamo to do one of two things: either (*a*) to regulate itself so as to send a *constant current* or a current of uniform strength through the external circuit, although the resistance may be considerably varied: or (*b*) we may require it to maintain a *constant potential* at the extremities of the external circuit—that is, at the brushes—under like variations of resistance A machine cannot be constructed to fulfil both these requirements, and we will first consider the best of the many methods of maintaining a constant potential. This consists in the combination, in one machine, of the series and the shunt methods of winding. The simplest way, perhaps, of viewing the arrangement, is to consider the machine as a shunt-wound one, having added to it, round the magnet-limbs, a few turns of wire in series with the external circuit. Then, when the external resistance is made very low, and, as a consequence, the current in the shunt coils reduced to almost nothing, the magnetic effect of the series coils becomes a maximum, so that the opposite variations in these two sets of coils tend to keep the field more or less constant. It is clear that the success attending this combination will depend largely upon the proper proportions being given to the shunt and series coils, and in order to ascertain what these proportions are or should be for any particular case, we will now introduce a convenient method by which the variation of the E.M.F. developed by a dynamo under varying conditions can be studied.

Let us start with the case of a series machine, driven throughout the experiments at a constant speed, and joined up to a set of suitable known resistances which can be varied as desired. The resulting current can be measured by any suitable ammeter, and, the resistance of the machine and of the external circuit being known, the whole of the E.M.F. developed can be calculated as the product of amperes and ohms. We thus obtain the amperes of current flowing and the whole of the volts of E.M.F. developed, and these two quantities may be similarly found for any number of values which we choose to give the external resistance.

For instance, we might start with the external resistance very high and reduce it by suitable gradations until it becomes as low as safety to the machine will allow. A table might then be made showing the number of amperes flowing at every stage and the volts corresponding thereto. But by means of the 'squared paper' previously referred to, the whole of the experiments can be shown graphically

FIG. 161.



in the form of a curve, known as the 'characteristic curve' of the particular machine experimented with. Fig. 161 represents such a curve, taken from a series machine, driven at a constant speed. The volts calculated are measured off in vertical distances or ordinates, and the amperes in horizontal distances or abscissæ, the intersection of *corresponding* ordinates and abscissæ being points on the curve. The length of the side of a square in the figure represents 10 volts or 10 amperes, but in practice it is better to use a larger sheet of paper divided into a greater number of squares, one side of each square representing 1 volt, or 1 ampere as the case may be. One of the experiments with this machine showed that 70·6 volts were developed when 18·2 amperes were flowing, and the point A on the curve is the result of this particular experiment. It is the point of intersection of the two straight lines, C A and D A, drawn at right angles to O Y and O X respectively, C A being 18·2 units and D A 70·6 units, in length (the unit being one-tenth of the side of one of the squares). Another experiment, which determined the position of the point B, showed that 42 amperes were flowing when 87·4 volts were developed; therefore the distance E B is made equal to 42 units, and F B to 87·4 units. Other points were fixed by similar experiments, and by joining these points together the curve was obtained. Considerable care must be exercised in performing the necessary experiments to determine one of these curves, and in the region of any decided change in the curvature the number of experiments must be greater than in the more uniform portions of the line. Notwithstanding, however, the exercise of the greatest possible care, some of the points are usually placed a little out of position, owing to experimental error. But experience and theory teach us that zigzag deviations never appear in the curves of dynamo machines, so that when the points do not lie exactly on a regular curve, we can, to a certain extent, correct experimental errors, by striking what may be called an average, with the aid of a flexible ruler.

Were the amperes and volts to increase in the same proportion throughout, the 'curve' would be a straight line; but with every self-exciting series dynamo we get a curve somewhat similar to the one here given—that is to say, with the first part ascending rapidly, then a decided bend, followed by a fairly straight portion making a smaller angle with the horizontal. It has already been pointed out that although the E.M.F. rises as the current flowing round the field-magnets (and, therefore, as the strength of the field) increases, a stage is reached when a given increase in the current does not give a proportionate increase in the field. This happens when the iron in the field-magnets becomes saturated, and it is at this stage that the decided bend in the characteristic curve shows that the amperes are increasing faster than the volts.

It sometimes happens that by merely glancing at a curve we can criticise the design of a machine in some important respects; for instance, the effect of having too little iron in a machine would be to make the bend occur earlier than it really should do. Other points of criticism will manifest themselves presently.

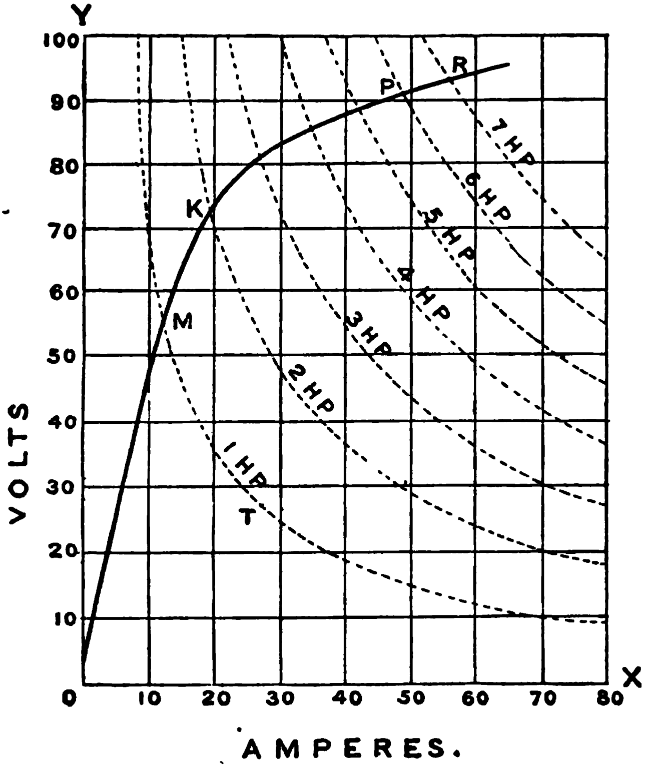
Reverting to fig. 161, it will be seen that the curve commences, not exactly at the point O, but at a point a little way up the vertical line, thus apparently indicating the existence of a small E.M.F. before the current commences to flow. This actually is the case, and results from the existence, in the field-magnets, of residual magnetism, which provides a weak field and produces a small E.M.F. at the terminals before the circuit is completed.

The two quantities—current and E.M.F.—plotted in this curve, are those which, when multiplied together, enable us to estimate the amount of power being developed in the whole circuit, for the product of one volt and one ampere is one watt, which is the electrical unit of power, or rate of expenditure of energy, and 746 watts correspond to one horse-power. It follows that we can select any point on the curve and readily calculate what power was being developed in the circuit at the particular moment that the point was determined; for instance, during the experiment which determined the position of the point A, the power developed was 70·6 × 18·2 = 1,284·92 watts.

Such calculations can, in a measure, be avoided by the addition of another set of curves cutting the characteristic at points which correspond to a certain horse-power or fraction of a horse-power. Fig. 162 is a copy of fig. 161, with a number of these horse-power curves added in dotted lines. At the point M, where the characteristic cuts the 1 horse-power line, the product of volts and amperes is equal to 746 watts, while at K it is equal to 2 × 746 = 1,492 watts. Now, if the dynamo is driven at a higher speed, the E.M.F. for a given current will be greater—that is, the vertical distances will be relatively greater than the horizontal ones as the speed is increased, and a curve somewhat similar in shape, but placed above the existing one, will be obtained. Several curves may thus be plotted on the same sheet of paper, and the power developed at different stages in each case readily compared, by reference to the horse-power lines.

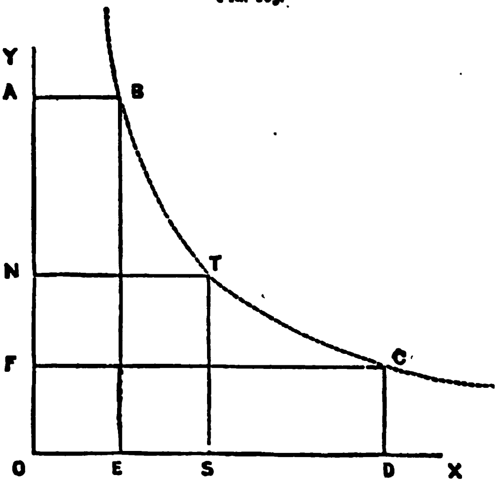
Although it is possible to apply to these horse-power lines a rather high-sounding mathematical definition, they may be constructed by a simple process. As an example let us take the 1 H.P. line in fig. 162; T, the nearest point to O, will be equally distant from O X and O Y—that is to say, the perpendiculars drawn from T to O X and O Y will be equal. These perpendiculars are shown in fig. 163, where T S = T N, and their product T S × T N must be equal to 746 units, since T is a point on the curve.

FIG. 162.



Now NTSO is a square, all the sides are equal, and therefore $TS \times TN = TN^2 = ON^2 = 746$, or $ON = \sqrt{746}$. (The unit in fig. 162 is one-tenth of the side of a square, and in every case the unit is that length taken to represent one volt or one ampere.) If, therefore, we take ON and OS equal to $\sqrt{746}$—that is, 27·3 units in length, and draw perpendiculars from N and S, their intersection in T will give the first point on the curve. Then, if any convenient number of rectangles, equal in area to the square, be constructed, the product of two adjacent sides will equal $ON \times TN = 746$. For instance, the rectangles OB and OC are equal to the square OT (OA and OD being each twice the length of ON, and OF and OE being half that length). Therefore, since $AB \times BE$ and $CD \times CF$ are each equal to 746, B and C are points on the curve. This method illustrates the principle in a simple manner, and quicker methods of finding pairs of lines whose products are equal will suggest themselves (Euclid, III. 36). The side of the square determining the first point on the 2 H.P. line will be equal to $\sqrt{(2 \times 746)} = \sqrt{1492}$, consequently the other points can be found in the same way as before.

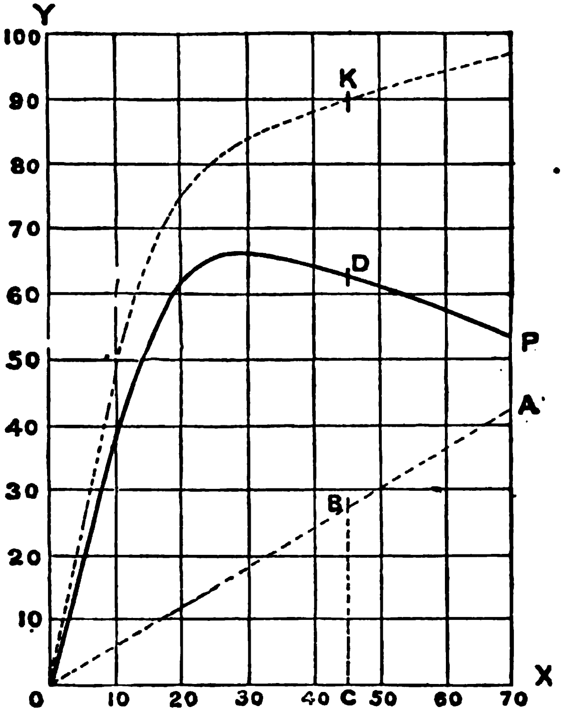
Fig. 163.



It will be remembered that the characteristic in fig. 161 was constructed by measuring the amperes, and calculating the total volts; but it is less troublesome to join up a voltmeter and measure directly the volts *at the terminals* of the dynamo, and then plot a curve showing the potential difference at the terminals (instead of the total E. M. F.), corresponding to various values of the current. In fact, this latter curve, usually called the external characteristic curve, is the more useful of the two, for in practice it is the external potential difference which concerns us most.

In fig. 164 the curve O P is the *external* characteristic, obtained from the same machine as the previous curve, running at the

FIG. 164.



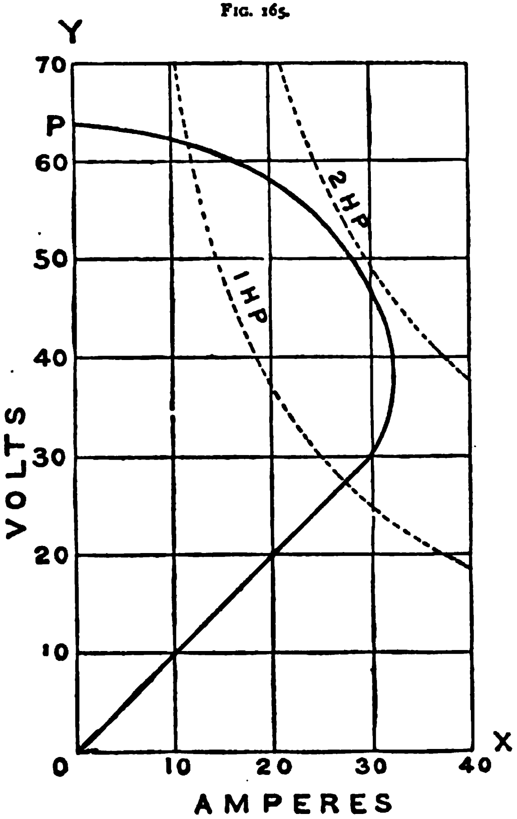
same speed. The bend is now even more clearly defined; in fact, after a certain point, the potential difference falls as the current is increased. One reason for this bending down is, as we have said, the magnetic saturation of the iron, and it is also partly caused by the heavy current in the armature distorting the field. The curve shows us then, at a glance, the particular current strength at which we can get the maximum external potential difference at a given speed, and, of course, by inserting the horse-power lines, we can also see the amount of power absorbed in the external circuit. Now the remainder of the E.M.F. is absorbed in overcoming the resistance of the armature, and since this armature resistance is constant, this portion of the E.M.F. (found by multiplying the armature resistance and the current) will always be proportional to the current flowing. In fact, if we plot the 'curve' for current and E.M.F. expended in the armature, we get the straight line O A. And, further, if at any point, say C, we add together the vertical distance, C B, from the base line to the line O A, and C D, the vertical distance to the external characteristic, we get a line proportional to the whole E.M.F., giving the point K on the original total characteristic. In this manner we can construct the total characteristic curve, now shown as a dotted line; or, given this curve, we might draw the line O A, and by subtracting, deduce the external characteristic.

The greater the armature resistance the greater will be the fall of potential along it, and therefore also the greater will be the angle which O A makes with the horizontal. In fact, the tangent of this angle is proportional to the armature resistance, for $R = \frac{E}{C} = \frac{BC}{OC} = \tan BOC$.

If this angle happened to be 45°, we should know that the armature resistance is 1 ohm, for the tangent of 45° is 1. In the present case the angle is 31°, the tangent of which is 0·601; therefore the armature resistance is 0·601 ohm.

Coming now to the case of a shunt-wound dynamo, if we plot the curve having ordinates proportional to the electromotive force, and abscissæ proportional to the current in the shunt coils, a somewhat similar result is obtained; but the 'external' characteristic is very different, as will be seen on referring to fig. 165, which is the curve obtained from a shunt dynamo, the vertical distances being proportional to the potential difference at the terminals, and the horizontal distances to the current in the external circuit. As before, the scale taken is such that a side of a square represents 10 volts or 10 amperes. If we suppose the series of measurements to be commenced when the external circuit is disconnected and its resistance therefore infinite, the E.M.F. at the terminals of the machine will have its maximum value, and we shall obtain P, the highest point on the curve. With this particular machine running at a certain constant speed, the maximum E.M.F. happened to be 63·5 volts, and as, of course, no current flowed in the external circuit, the point P is placed on the line O Y, at a distance of 63·5 units above O X. When very high resistance is introduced, so as to allow just a feeble current to flow in the external circuit, the E.M.F. at the terminals falls slightly, and continues to fall as the resistance is reduced and the current consequently increased. At first the amount of current abstracted from the field-magnet coil makes but little difference to the strength of the field, and therefore the E.M.F. falls but slightly. But when the external resistance is so low that the current becomes about 20 amperes, the amount abstracted from the shunt begins to have a very decided effect upon the strength of the field. The E.M.F. then falls considerably, and, the current remaining fairly constant during a small range, the effect is seen in the curve as a sudden bend downwards, almost, in fact, a perpendicular line. The resist

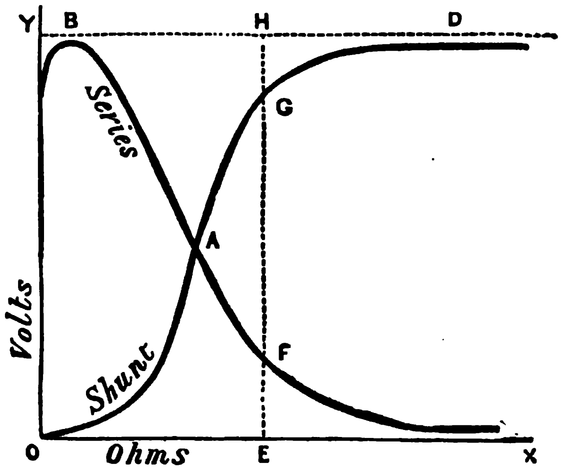
FIG. 165.



ance being still further reduced, not only does the E.M.F. fall, but also the current, giving the curve a turn *backwards*, until presently the field-magnets lose their magnetism, and when the terminals are short-circuited the curve terminates in the point O, E.M.F. and current being then reduced to *nil*. As the field-magnets, however, rarely lose the whole of their magnetism, a feeble current continues to flow after the terminals have been short-circuited, so that the curve should really end at a point some little distance from O along the line O X.

Although these characteristics give us a clear idea of the manner in which the external potential varies with the classes of dynamos referred to, we can better understand the method of combining, or, technically speaking, 'compounding,' the series and shunt windings to obtain self-regulation, by constructing and comparing other curves, which show how the external potential and the external resistance vary together, both in a series and in a shunt machine. As before, the ordinates (fig. 166) represent volts, but the abscissæ now represent ohms. The figure shows two curves, one for a shunt and the other for a series machine, both starting at or near the line O Y, when the external resistance is very low.

FIG. 166

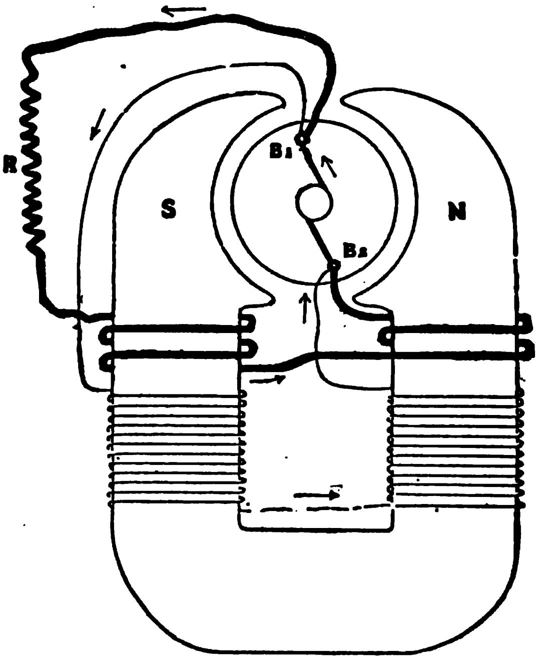


In the case of the shunt machine, the curve shows the E.M.F. to be very low at first, gradually rising for a short distance as the resistance is increased, until at a certain stage it ascends suddenly, this, as we know, occurring when the external resistance is great enough to allow the field-magnets to become strongly magnetised. On the other hand, the curve from the series machine is at its highest point B, when the resistance is low, and it falls almost in the same manner as the other curve rises. This curve can hardly start on the line O Y, because, of course, when the resistance between the terminals is *nil*, no difference of potential can exist, but it quickly reaches the highest point as the resistance is increased. Now if in one machine it is possible to so proportion the shunt and series windings that the maximum effect of the series coil is equal to the maximum effect of the shunt coil, and also that the effect of the series coil diminishes in the same proportion as the effect of the shunt coil increases, these two windings will counterbalance each other through a considerable variation of resistance, and the result will be a constant external potential difference. The first condition would make the height of the highest points on each curve equal; while if the second condition were attained, the slope downward of the one curve would exactly correspond to the slope upward of the other. And at any point, such as E, the E.M.F. due to the series coil added to that due to the shunt coil, that is, E F + E G, should give us the vertical line E H equal to the height of the highest point on each curve. Likewise, the point of intersection A should be midway between B D and O X, and the heights of the two curves added together throughout should produce the straight line B D. Then the E.M.F. at the terminals being constant, the current will vary regularly with the resistance, and we shall consequently obtain a straight line for the characteristic curve of the compound-wound machine. It is evident that if the series coil acts too powerfully the effect will be to raise the point B, that is, to make the E.M.F. higher when the external resistance is low and the current strong, than when the external resistance is higher; and *vice versâ*.

Since, however, the effect of an alteration of the speed of rotation of the armature is so different in the case of a series as compared with a shunt machine, a dynamo compounded in the manner just described is only self-regulating at a given speed ; for at any other speed the two windings do not compensate each other.

In the case of a series machine, if, for instance, the speed were doubled and the external resistance increased sufficiently to keep the current the same, the strength of field would remain unaltered and the E.M.F. would be increased almost, but not quite, two-fold by the doubled speed. On the other hand, if, with a shunt dynamo, by increasing the external resistance we maintain the external current constant when the speed is doubled, the current in the shunt coil, and therefore the strength of the field, increases instead of remaining the same as does that of a series dynamo. While, if at the doubled speed the resistance were reduced to make the current in the shunt coil the same as at the lower speed, the external current would be greatly increased in strength. Therefore

FIG. 167.

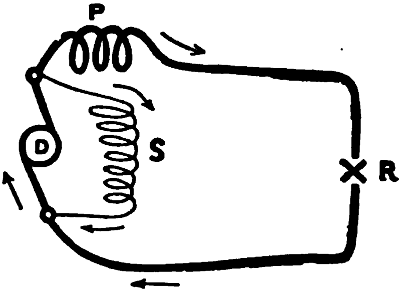


because of these different effects of an alteration of speed on the series and shunt windings, the dynamo will only regulate perfectly when driven at the particular speed for which it was compounded. In practice the speed at which the machine is to run is usually determined beforehand, then at this speed the shunt coils alone must be able to provide a sufficiently strong field to develop at the terminals the required E.M.F. when the external circuit is disconnected, while when the external resistance is made as low as it will be in actual working the ampere-turns in series should be able to maintain this same field.

The connections of a compound-wound dynamo, and the paths taken by the current through its coils, are typically illustrated in fig. 167.

As in previous similar figures, B_1 B_2 are the brushes; at B_1 the current generated in the armature divides, part going through the shunt coils wound on the lower parts of the limbs of the field-magnet and thence returning to the brush, B_2. The remainder passes through the external circuit R, then round the series coils on the upper part of the field-magnet, and thence to the brush, B_2. The shunt coils are wound with comparatively fine wire, but, of course, the resistance of the series coils must be kept very low as they carry the main current, and they are composed, therefore, of a few turns of very thick wire. The relative positions of the two sets of coils is not always that shown, the series coil being sometimes wound outside and sometimes inside the shunt coil; but this not very important point is decided by convenience in construction rather than by theory.

FIG. 168.



To render the path of the current even more easily understood, fig. 168 is added; R is the external circuit, D the armature, S the shunt coil, and P the series coil.

In practice so successful are designers and manufacturers, that it is not uncommon to find a machine which, when driven at its proper speed, gives a straight line as its characteristic, through a range of 100 amperes or even more.

The foregoing method is the one commonly adopted for compounding dynamos to give a constant external potential, notwithstanding variations in the external circuit. We shall not refer to any other methods, many of which are only theoretically possible, but may briefly mention some interesting experiments of the Drs. Hopkinson which bear somewhat upon this point. They disconnected the field-magnet coils of a certain machine, and, having placed the brushes in the position for an undistorted field, connected them to the terminals of a Siemens dynamometer. Then, when the armature was driven at 1,380 revolutions per minute, the current, due solely to residual magnetism, was 52 amperes; but on giving the brushes a slight forward lead, the current fell almost to zero, because the field due to the current in the armature was then opposing that maintained by the residual magnetism. But when a backward lead was given to the brushes, the polarity of the armature was shifted round so as to enhance the residual magnetism in the pole-pieces; the armature, in fact, now generated its own field, and a current of 234 amperes was obtained. Since the field in such a case is almost proportional to the current flowing in the armature, which increases as the external resistance falls, such an arrangement would regulate for constant potential; but it is not practicable owing to the destructive sparking which arises in consequence of the coils being short-circuited by the brushes while fairly active.

CHAPTER X.

DIRECT CURRENT DYNAMOS—*continued.*

We will now illustrate and describe some of the best modern direct-current dynamos, selecting only such as are of first-class design and construction, and directing attention in each case to those details which are likely to prove most instructive in showing how theoretical principles are applied, and how, in practice, mechanical and economical considerations sometimes cause a deviation from forms which a narrow theory might show to be the best.

The student is recommended to pay particular attention to the methods adopted for securing mechanical strength and durability. It may be observed, for example, that it is quite as important to prevent the conductor being stripped from an armature, as to efficiently insulate it. Again, while a waste of power, such as is evidenced by the heating of the iron core by eddy currents, is to be deprecated, any waste which shows itself in such a manner as the undue heating of bearings is equally, or even more, to be avoided. In both cases the power applied to the shaft is wasted—in the former case after, and in the latter case before, it has been transformed into electrical power.

Fig. 169 illustrates a dynamo constructed by Messrs. W. T. Goolden & Co., the armature being of the Gramme ring[1] type, and the field produced by an inverted horse-shoe magnet. This particular machine is compound-wound, and the arrangement is therefore similar to that depicted in fig. 167. A vertical section of the machine at right angles to the shaft is given in fig. 170. The bed-plate is of cast-iron and includes a solid piece, D, in the centre, directly under the armature and field-magnet, to form the

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[1] The core of this type of armature is now made much longer than formerly and the armature is frequently and more aptly called a cylinder armature.

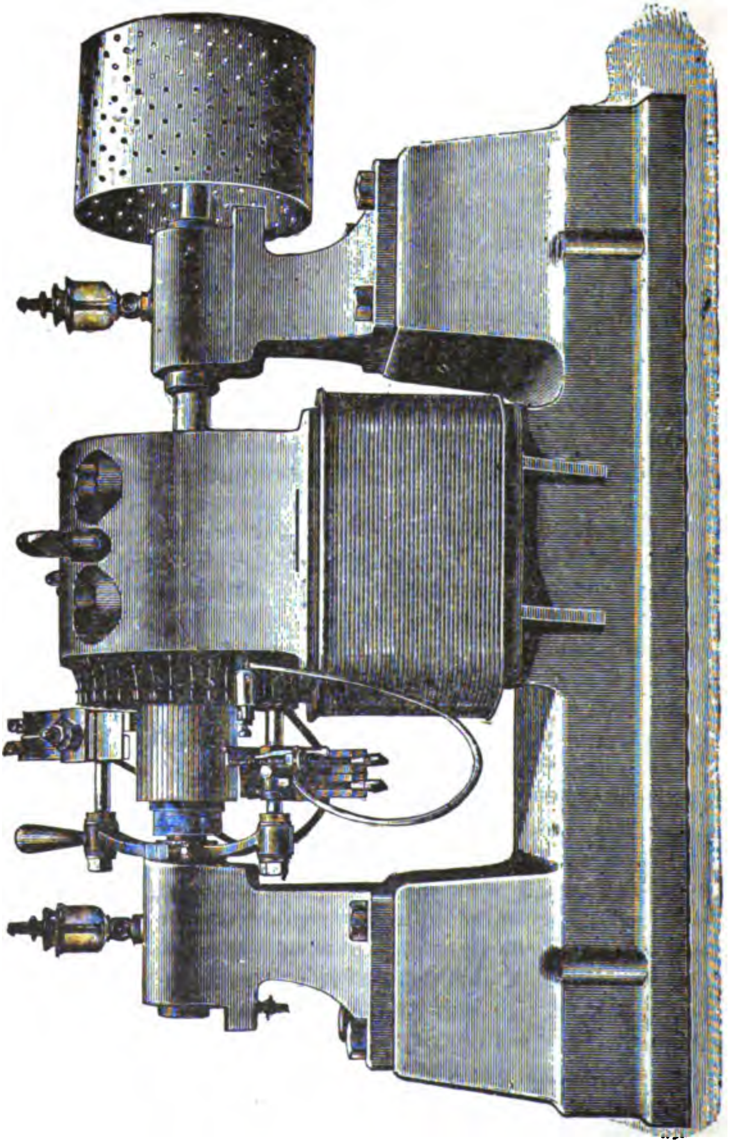
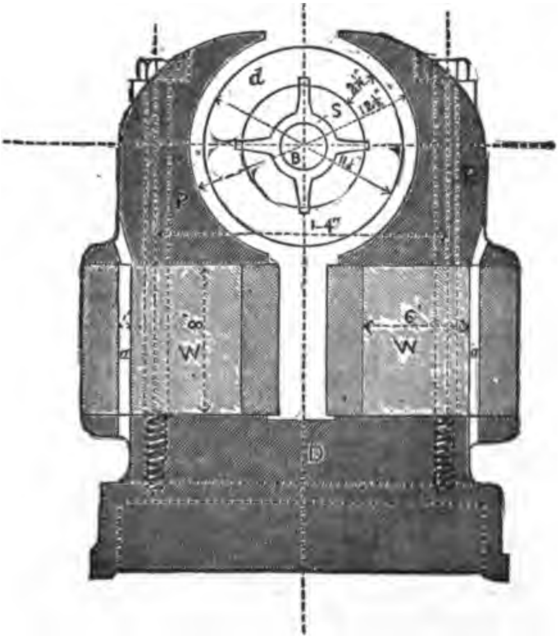


FIG. 169.

yoke of the latter. But wrought-iron is employed for the actual cores round which the field-magnet coils are wound, each core, W W, consisting of a slab of special soft hammered scrap-iron; thus giving the advantage, previously referred to, of economising copper wire, by obtaining the requisite magnetic conductivity with the minimum sectional area. The pole-pieces are of grey cast-iron, and the sectional area of all the cast-iron portions is sufficiently increased to compensate for the lower permeability as compared with that of the excellent iron forming the core. It is, however, evident that as the lines of force begin to pass into the armature from the bottom of the pole-pieces, fewer lines pass through the upper part of it than through the lower, and consequently there is no advantage in having the iron of the same thickness throughout. The pole-pieces, P P, are therefore so

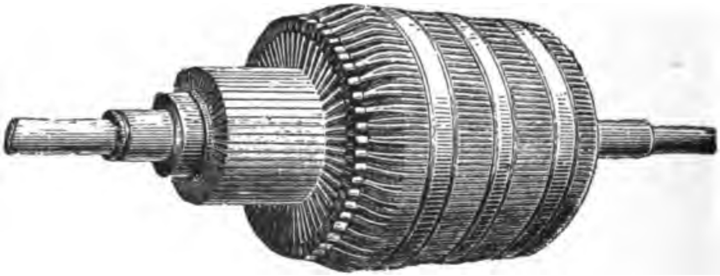
FIG. 170.



shaped that they taper away towards the horns at about the same rate that the number of lines of force passing through them diminishes in consequence of the lines leaving at the various portions of the face, thus giving the same magnetic density throughout. Two long bolts pass through each of the pole-pieces and the wrought-iron cores, screwing, at their lower extremities, into the solid portion of the bed-plate which forms the yoke-piece, and thus holding these parts firmly together. The coils are wound so as to leave a space between the wire and the outer face of the wrought-iron core, as shown at *a a* in the figure, forming thereby a very effective means of ventilation, for as the wire gets warm its heat is imparted to the air inside this space, and this air rising, a constant circulation is maintained and the heat carried off by a steady draught of cold air.

The series winding consists of twenty-five convolutions of copper strand, composed of nineteen No. 15 wires (standard wire gauge), a stranded conductor being much more flexible than a solid one, although it occupies a little more space. Over this is wound the shunt coil, which consists of 2,712 turns, its resistance being 20·6 ohms. In order to afford a means of obtaining this resistance with this particular number of convolutions, two sizes of wire are employed—viz. Nos. 15 and 16, S.W.G.—the respective lengths of these two wires being adjusted to satisfy the conditions.

FIG. 171.



The complete armature is shown in fig. 171. The core consists of a number of very thin flat rings of well-annealed charcoal iron, as shown at *d* in the sectional view (fig. 170). The outer diameter of the ring or disc is 11½ inches, and its inner diameter

9¼ inches. Four rectangular notches are cut out of each disc, at equal distances round the inner edge; a sheet of thin paper insulates each disc from its neighbours, the whole of them being held tightly together by two rigid end-plates. Upon the Bessemer steel shaft B is keyed a gun-metal spider, S, having four radial arms, its length along the shaft being equal to that of the finished core, and the extremities of the arms fitting accurately into the notches in the discs The student will remember the necessity for avoiding, as far as possible, the use of iron in the interior of a Gramme ring, and will therefore understand the reason for making the spider of gun-metal. It should also be borne in mind that although it is absolutely necessary to efficiently insulate the thin plates into which the core is divided, yet, in consequence of the thinness of the discs, the space occupied by the insulation forms a considerable portion of the whole, whence the magnetic resistance is proportionally increased. In this particular case, 80 per cent. of the core consists of iron and the rest of paper.

The armature conductor consists of cotton-covered copper wire of No. 9 standard wire gauge, lying round the core in one layer and offering a resistance, from brush to brush, of 0·048 ohm.

There are two convolutions in each section, the adjacent ends of neighbouring convolutions being soldered to radial lugs projecting from the commutator bars, as shown in fig. 171.

There are 152 such sections, and, consequently, seventy-six bars in the commutator, these bars being of hard drawn copper insulated from each other by mica strips 0·75 mm. in thickness. Mica is almost the only material now used for this purpose, for which it is eminently suitable, because of its excellent insulating properties, its great durability, and its practically perfect cleavage, in consequence of which it can be procured of any desired thinness.

As the length of conductor parallel to the shaft is considerable, there is a risk of its bulging out when rotated at a high speed, a tendency which would be assisted by the rise in temperature and consequent expansion of the wire, caused by the current itself. Any such bulging out or stripping of the conductor is prevented by binding the armature with several turns of fine strong wire in three places, as shown in fig. 171.

The speed of the machine is 1,050 revolutions per minute, at which it is capable of giving a current of 75 amperes, with an E.M.F. at its terminals of 100 volts.

The brushes consist of flat tough copper strips, fixed in adjustable holders, which are carried by the horizontal arms projecting from the rocking lever, as shown in fig. 169. This lever is provided with an insulating handle, by means of which it can be rotated in either direction round the axis of the shaft, thus affording facilities for altering the lead of the brushes to suit the requirements. It is carried on a projection from the standard supporting the bearing, and is made in two pieces bolted together, so that it can be readily tightened up on its bearing, or, if necessary, removed. The horizontal arms are insulated from the lever by hard fibre collars; and spiral springs, with adjusting screws, are provided for varying the pressure of the brushes on the commutator, the pressure being always as light as is consistent with reliable contact.

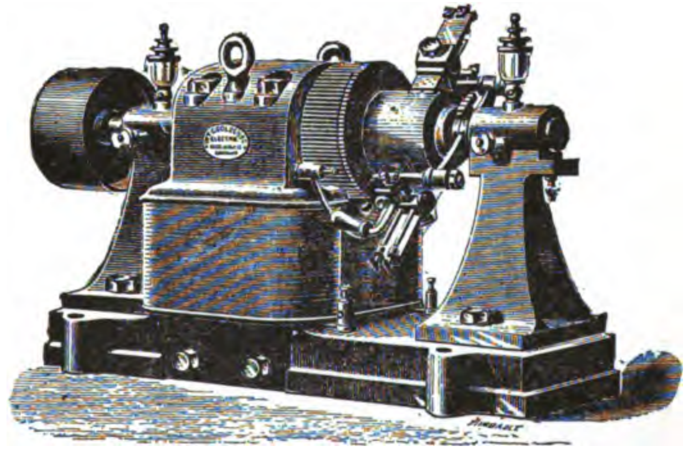
The brushes are shown lifted from the commutator; and it will be observed that they can be adjusted along the bars, so as to press upon different parts when the machine is running, and thereby distribute the wear. The commutator is turned up perfectly true in a lathe with a fine tool which cuts the copper cleanly and does not drag or burr it over the mica strips.

The shaft-bearings are of phosphor bronze, and the rim of the pulley is perforated to afford a better grip for the belt.

Most machines are, however, now made of the drum type, and fig. 172 illustrates a drum-armature dynamo constructed by the same makers. The general proportions of the field-magnets are somewhat similar to those of the machine already described, but the method of fixing the parts together differs. The two vertical bolts passing through each of the pole-pieces extend only about half way into the wrought-iron cores. Each core is lengthened a little, and, fitting into a slot in the cast-iron bed-plate, is held firmly in position by two horizontal bolts passing through the solid parts of the casting. The core is built up in a manner somewhat similar to that adopted for the ring machine, but the radial depth of the discs is somewhat greater, and the driving-spider is made of iron instead of gun-metal. The armature conductor is composed of two No. 11 wires wound on together in parallel, and the resistance from brush to brush is 0·0341 ohm. The commutator has eighty bars. The field-magnets are compound wound, the series-winding comprising sixty-six turns, each of which consists of two No. 6 wires in parallel; and the shunt coils, which are wound over the series coils, contain 2,600 convolutions of No. 15 wire, having a resistance of 15 ohms.

At a speed of 1,180 revolutions, a current of 85 amperes, with a potential difference of 80 volts at the terminals, is delivered.

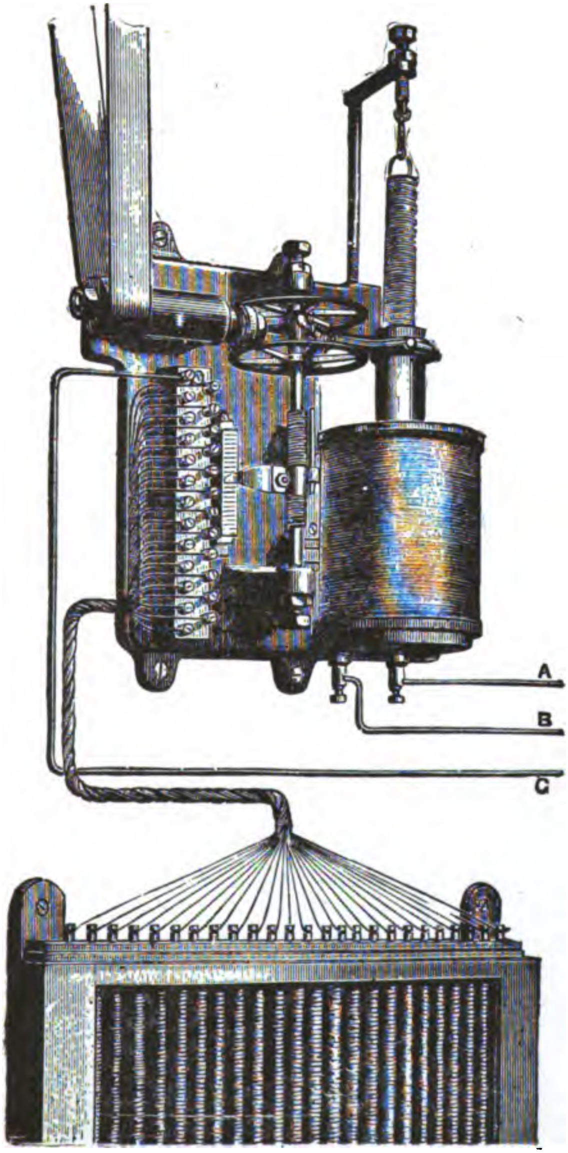
FIG. 172



In some cases, where the current generated is very heavy, the active conductor consists of thick copper bars, which are laminated to reduce the eddies in them, the bars being, as a rule, divided longitudinally into five sections.

These dynamos are compounded to give a constant potential when driven at a certain speed, but for cases where the speed is liable to variation, and where, therefore, a compound machine cannot be used, but where a constant E.M.F. or a constant current is required, or where it is desired to maintain a constant current although the external resistance varies, an automatic mechanical regulator is employed. This regulator varies the strength of the field by altering the strength of the current flowing through the field-magnet coils. A set of resistance coils is placed in series with the field-magnet coils of a shunt-wound machine, and an arrangement adopted for cutting out some of these coils when the current or the potential difference falls too low, or inserting more of them when it becomes too high. The complete set of regulating apparatus is shown in fig. 173. The resistance coils, which are shown at the lower part of the figure, consist of spirals of bare iron wire, supported by a wooden frame in such a manner as to afford great facilities for cooling when heated by the passage of the current. An important part of the apparatus is the large solenoid, placed with its axis vertical. If it is desired to maintain a constant potential under varying conditions, this solenoid consists of many turns of fine copper wire, the two wires A and B, leading from its terminals, being joined to the brushes of the dynamo. An iron core, suspended by a spiral spring, projects a short distance into the upper portion of the solenoid. When the potential rises the current increases and sucks this core further down; while a fall of potential allows the antagonistic spiral spring to withdraw the core a little. From the upper portion of the core projects an arm, its end playing between two light wheels which are rigidly fixed on a common vertical spindle, this spindle having a small amount of end-play. The tension of the spring is so adjusted that when the potential is at the required value the upper wheel just rests upon the arm projecting from the core, and both wheels are kept clear of a small rubber-faced disc on the end of a short horizontal shaft, which is driven by a belt from the main shafting. If, on account of a rise in the potential, the core with its projecting arm is sucked down, the two light wheels drop, and, the upper one engaging with the rubber disc, is rapidly rotated. A screw thread is cut in the vertical spindle some little distance below the wheels, and on it is a rather long screw-nut which is prevented rotating, and which, therefore, travels up or down according to the direction of rotation of the vertical spindle. A flat spring projects from this nut, its end passing over a set of contact pieces to which are connected the various resistance coils, one end of the series of coils being joined to the upper contact piece, and the other end direct to the vertical spindle and screw nut, which are also in connection with the terminal B. The arrangement is

FIG. 173.

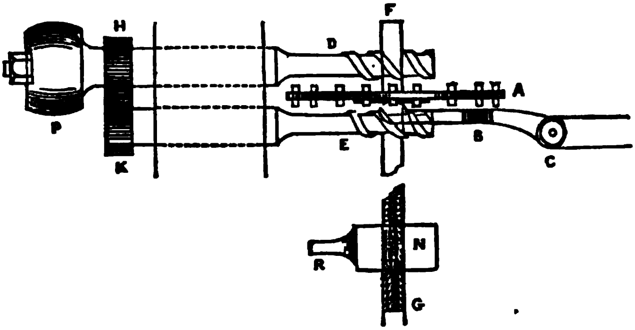


such that the motion imparted to the spindle, due to an increase of E.M.F., moves the flat spring in the direction which throws more resistance in series with the field-magnet coils, while if the core is moved upwards, the lower wheel engages with the friction disc and rotates the spindle in the reverse direction, reducing the resistance in the field-magnet circuit.

The solenoid is subject to the same heating error as a voltmeter, and to minimise this it is more frequently wound with fairly thick wire, the temperature of which rises but little, and the necessary resistance is obtained by joining in series with it German silver coils, which have a lower temperature coefficient, and, being left bare, dissipate heat readily. When the apparatus is required to maintain a constant current, the solenoid is wound with thick wire, and is joined up directly in the main circuit; the rise and fall of the main current which passes through it acting in the same way as a rise and fall of potential at its ends. The small horizontal shaft is driven at about 400 revolutions per minute, and the nut carrying the contact spring can then travel over the whole range in about ten or twelve seconds. The flat spring is so broad that the circuit is never broken during the movement of the spring, and a large number of coils is employed in order that the increase or decrease of the resistance shall take place gradually. The weak point about the apparatus, as depicted in fig. 173, is the means adopted for imparting circular motion to the light wheels; for, although the friction between the rubber disc and the wheel rim is at first quite sufficient, it becomes uncertain and unreliable if the rubber gets dirty or covered with oil. To overcome this difficulty an entirely different gearing has been adopted in the later apparatus, the essential parts of which are shown in fig. 174. R is the contact spring, carried by the nut N, working upon the screw shaft G, up and down which the nut travels according to the direction in which the screw is turned. The screw forms the lower part of the vertical spindle F G, upon the upper part of which is fixed a pin-wheel A, that is, a flat disc having a number of pins fixed parallel to its axis at equal distances round its circumference. Behind the spindle and parallel to the plane of the disc are two endless screws D, E, the upper one being at the end of the shaft, which is driven by a belt on the pulley P. By means of the equal spur wheels H and K, the lower shaft is driven at the same velocity as the upper one, but in the opposite direction. The arm projecting from the top of the core of the solenoid is pivoted at C, and forked from the point B, the adjustment, as before, being such that when the current or potential is at its proper value, the pin-wheel rests on the extremities of the fork, just midway between the two revolving screws. Any movement of the core raises or lowers the supporting arm, thus lifting the pin-wheel or allowing it to fall, so that the pins then gear either with the upper or the lower screw, and communicate a circular motion to the vertical spindle, in the one direction or the other as the case may be.

Within certain limits, the E.M.F. or current which the regulator maintains can be varied by altering the tension of the spiral spring

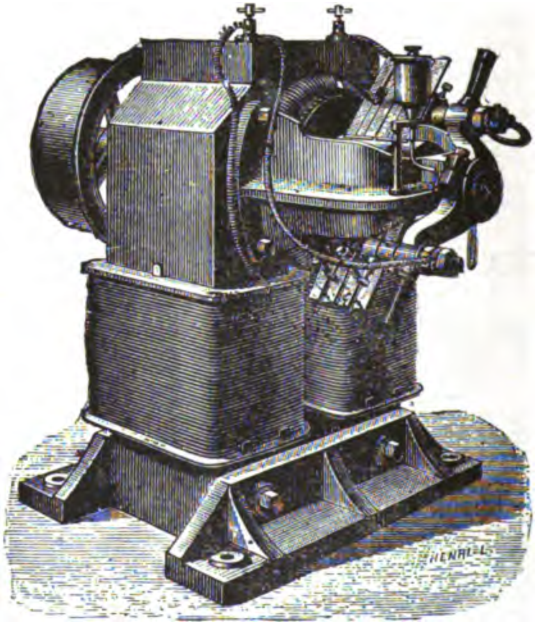
FIG. 174.



(fig. 173), and as this spring is a very important factor in the smooth working of the apparatus, considerable care is exercised in selecting it. In order to render the core perfectly astatic, resting decidedly in any required position, it is necessary for the pull of the solenoid on the core and the antagonistic pull of the spring to balance each other, length for length, throughout the whole of the space travelled by the core—that is to say, suppose it experiences a sucking force which moves it two centimetres inwards, against the spring, the force of suction on the core in this new position must be greater by exactly the same amount that is necessary to extend the spring two centimetres. This rather difficult adjustment is so successfully accomplished that the core is perfectly astatic, gliding to any new position immediately the current changes, and floating there without any oscillation.

The 'Phœnix' dynamo is made by Messrs. Paterson & Cooper, and in two distinct forms, according to the circumstances under which the machine is to be employed. Where lightness of construction is imperative the field-magnets are made of wrought-iron, but where the weight becomes a matter of secondary importance cast-iron is used, its lower permeability being compensated for by using about two and a half times the amount of metal. The first of these machines, in which the aim has been to obtain a comparatively great electrical output for a minimum weight, is illustrated in fig. 175.

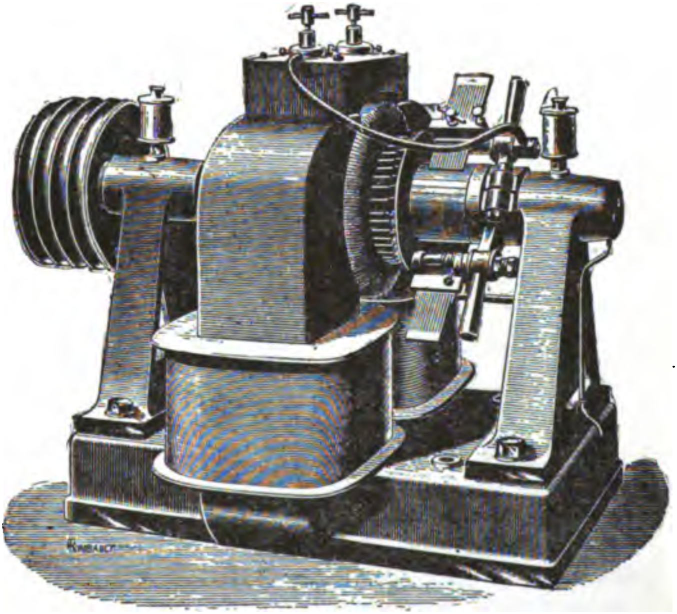
FIG. 175.



The field-magnet and bed-plate are the parts of the machine in which the greatest reduction in weight can be made, and the skill of the designer is shown in the manner in which this is accomplished without increasing the 'magnetic resistance' or diminishing the mechanical strength.

The field-magnet is of the horse-shoe shape, fixed with the poles uppermost. It is made of a single massive wrought-iron forging, which is slotted out to form the two limbs, sufficient metal being left at the bottom to form a substantial yoke. The space

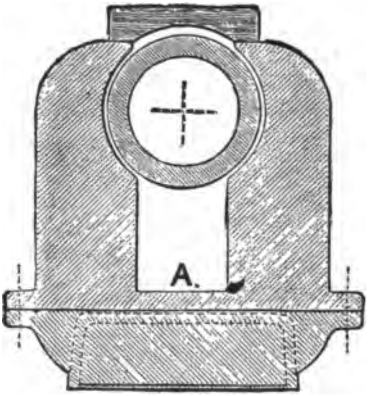
FIG. 176.



in which the armature revolves is then bored out. It will thus be seen that there is no break in the magnetic circuit, while, being of wrought-iron, the magnetic resistance is very low. Two cast-iron angle-pieces, which receive the foundation bolts, are bolted on to the yoke. The bobbins on which the field-magnet coils are wound are made of sheet-iron, with brass flanges, and are slipped over the limbs after the wire has been wound.

Two very strong gun-metal brackets are then bolted to the pole-pieces, for the purpose of carrying the armature bearings, which are of white metal, the whole forming a machine mechanically strong, but of comparatively little weight. It need hardly be said that this construction is expensive, and would not be warrantable in cases where there is a solid foundation available and where a little extra weight is immaterial. Fig. 176 illustrates a machine designed for use in such cases, a section through the field-magnets being shown in fig. 177. Here the field-magnets are of cast-iron, but of greater sectional area. Both limbs are in one casting, being connected together by the rather thin piece shown at A. This casting is securely bolted down to the cast-iron bed-plate, which, directly underneath the field-magnet, is solid and massive, and, together with the thin connecting-piece A, forms the yoke. The terminal board is fixed across the upper ends of the field-magnet cores. The bobbins are similar to those in the machine previously described, but the armature is carried on vertical cast-iron brackets bolted to the bed-plate. In the machine shown the pulley is grooved for rope-gearing.

FIG. 177.



The brushes are made of soft brass wire, and in the wrought-iron machine each brush is composed of four independently adjustable sections, the holder rocking round an extension of the gun-metal bracket.

The commutator consists of forty-eight bars, either of hard drawn copper or gun-metal castings, insulated with mica. Fig. 178 gives two views of this commutator, the upper half in each case being shown in section. Upon the steel shaft F is keyed a gun-metal bush, E, with a rim at one end recessed to receive the projections from the commutator bars B. The opposite corner of these bars is shaped to fit a steel ring, C, of triangular section, which is held tight home by the wrought-iron washer, D, screwed on to the gun-metal bush. The bars are insulated from each other by means of mica, and from the bush E and ring C by sheets of white fibre, indicated by the thick lines in the figure.

The armature is of the ring type, and its core is built up of a number of thin soft iron rings (D, fig. 179), insulated by paraffined paper, and the whole firmly clamped together between two end frames by three delta metal bolts, B, semicircular pieces being stamped out of the iron rings to fit these bolts. A gun-metal spider with three radial arms, G, is keyed on to the shaft at each end of the core, the bolts passing through their extremities as at F.

Fig. 178.

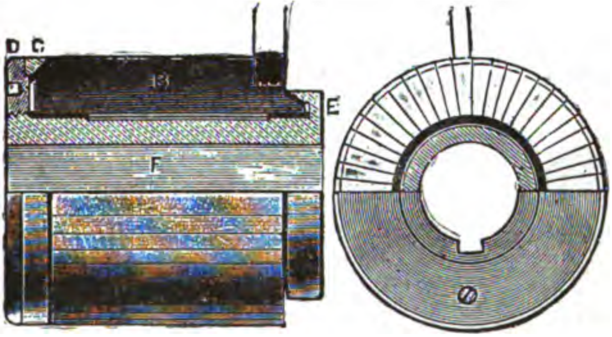
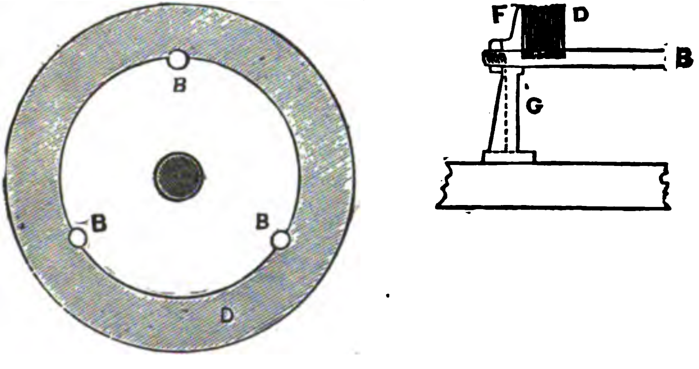
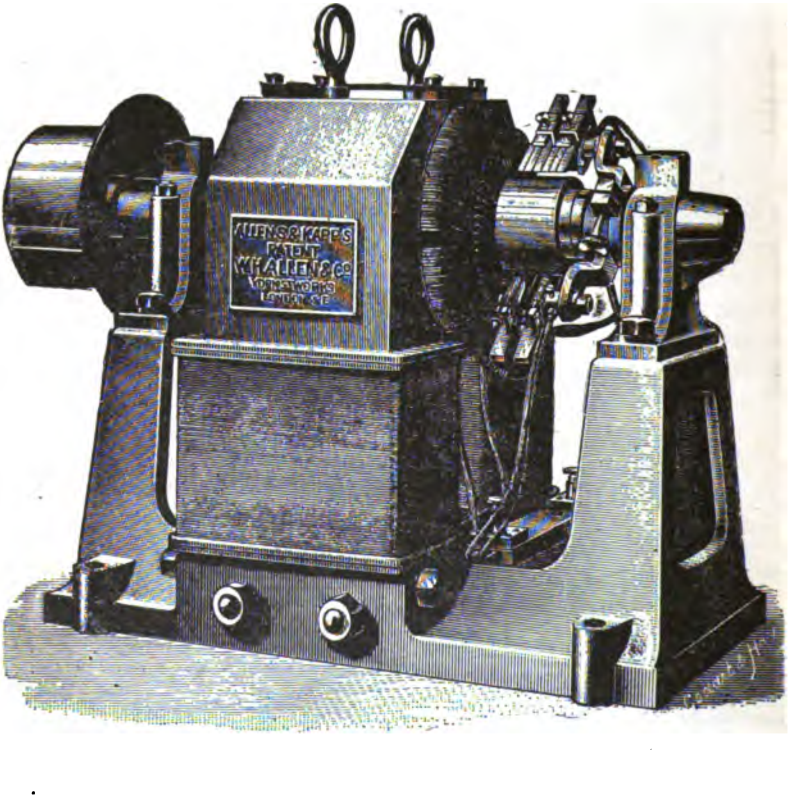


Fig. 179.

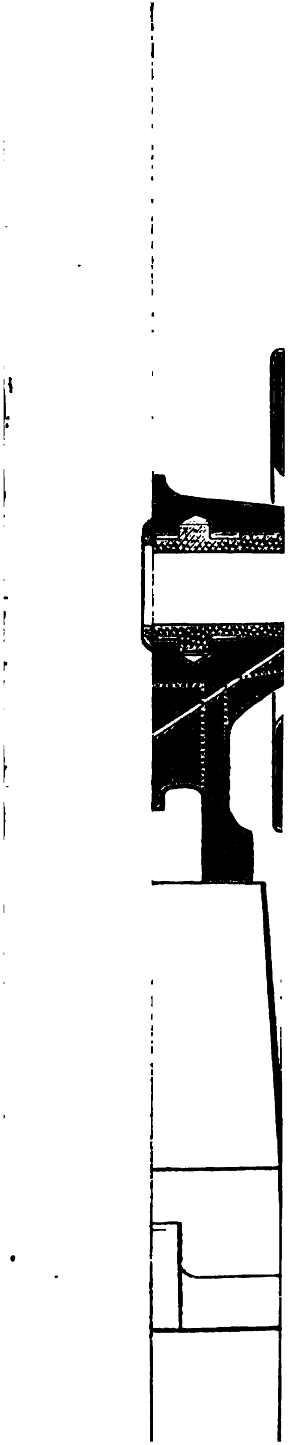


One size of the machine illustrated in fig. 176 has an output of 6,500 watts at 100 volts (65 amperes) when driven at 1,300 revolutions per minute. It is compound wound. The resistance of the armature is 0·03 ohm, and of the shunt coil 20·68 ohms, the series-turns being wound inside the shunt coil and having a resistance of 0·018 ohm. From these figures the student can calculate the power spent in the various portions of the circuit when the maximum current of 65 amperes is flowing.

FIG. 180.



A general view of the dynamo designed by Mr. Gisbert Kapp and constructed by Messrs. W. H. Allen & Co. is given in fig. 180. The field-magnets are also of the inverted horse-shoe pattern, which, it should be mentioned, Mr. Kapp was the first to use, the



object being to minimise, as far as possible, the magnetic leakage, as will be further explained presently. The armature in the machine illustrated is of the ring or cylinder type, but very few Kapp machines are now made with this class of armature. The drum and ring types are, however, very similar in external appearance, the chief difference being that due to the greater projection of the drum armature on account of the space taken up by the cross-connections.

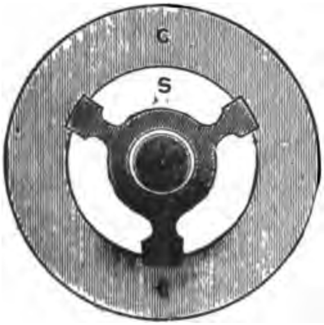
Figs. 181 and 182 illustrate many details of a recently-constructed drum machine, the former being a longitudinal section, and the latter an end view, half in section.

Each field-magnet limb, F, consists of a single slab of wrought-iron, the lower end of which fits into a slot in the cast-iron bed-plate. The bed-plate is solid at this part, and the vertical limbs are secured in position by two large bolts passing through, as shown in fig. 182. The pole-pieces are bored out circularly to form the space in which the armature is to revolve, and the horns *a a* securely pinned on. Upon the upper horns is fixed a board B, which acts as a cover to protect the armature. The field-magnet coils are of cotton-covered copper wire and are wound on frames or bobbins of thin sheet steel, *b b*, insulated with varnished paper, the bobbins being slipped over the cores after the wire has been wound.

The construction of the armature, which is well-designed and built with extreme care, is shown in fig. 181. H is a cast-iron hub, having three radial arms, W; it is securely keyed on to the steel shaft, its length along the shaft being equal to the length of the finished core. The extremities of the arms are planed to fit into notches in the core plates, C, as shown in fig. 183, which is a section through the armature core and hub taken at right angles to the shaft. The core-plates are of thin charcoal iron, and between them at equal intervals are placed three pairs of thicker rigid plates, which are kept a little distance apart by pieces of hard fibre, thus affording spaces for the circulation of air for ventilating purposes. The plates are separately well varnished and then built up, and while under high pressure between temporary end-plates, the core is slotted to receive the arms, W, of the hub. The lettering of figs. 181 and 183 corresponds. In the former, one arm, W, is shown directly below the shaft, while above it is the air-space, S, between the other two arms.

At one end of the shaft is provided a solid boss, K, and against this bears a cast-iron plate, P, in which are inlets, D D, for the passage of air. The core is held between P and a similar end-plate, R, which is secured by a steel nut, N, screwed on to the shaft. The ventilation is thus most efficient, for the air can enter through each end-plate by openings similar to D, and find its way along the spaces, S, between the hub and core plates, leaving by the openings between the rigid plates previously referred to.

FIG. 183.

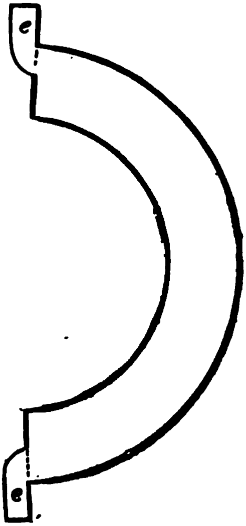


Before being wound the core is turned in a lathe to obtain a perfectly cylindrical and smooth surface. At intervals round the thicker plates there are projections, which serve to drive the conductor and prevent its being stripped. These projections are shown on the middle pair of plates in fig. 181, and, in addition to these horns, the completed armature is bound round in several places with thin strong wire which effectually overcomes any tendency towards bulging or stripping.

There are 204 active conductors round the periphery of the armature, each consisting of a straight strip or bar of copper, 0·0215 sq. in. in sectional area, insulated with a double cotton covering. They project to different distances over the edge of the core, and are soldered to the ends of peculiarly shaped copper strips which form the cross connections.

One of these connecting strips is shown in fig. 184. It is a stamping of sheet copper and forms almost, but not quite, a semicircle, because it is required to extend round the end of the armature just far enough to connect two bars which are almost at opposite extremities of a diameter. The connector is placed with its plane parallel to the plane of the core discs, and the two small end-pieces or tags, *e e*, are bent round at the part shown by the dotted lines until they are at right angles to the other portion of the strip The ends of the two conductors which are to be joined together are soldered to these pieces (*e e*). In fig. 181 the conductor A is connected to the tag *e*. Each section of the armature consists of two convolutions, that is, four active conductors, and the cross connectors occupy a comparatively small space, a section through the whole of them being shown at L L. Over the shoulder of each end-plate is fixed a cast-iron ring, T, with a wide deep groove in which the connectors are placed, each well insulated by being over-wound with tape treated with shellac varnish. There are fifty-one bars in the commutator, and the method of holding them in position is shown in the longitudinal section. They have two square notches, into which fit rings of hard vulcanised fibre, the sections through which are shown black in the figure, and it will be observed that there is a deep groove on the outer side of each ring. A gun-metal sleeve is keyed on to the shaft, one end fitting into the groove of one insulating ring, while a thread is cut round the other end for a nut, which, when screwed up home, presses a gun-metal ring into the groove of the other fibre ring. The commutator bars are insulated from each other by mica, and each brush is divided into two independently adjustable parts, this being a better arrangement than one wide brush, which would probably wear unevenly and, in consequence, cause a considerable variation in the amount of surface contact. The sectional view also shows the manner in which the rocking bar is carried round a groove at the end of the cast-iron standard, and the fixing of the horizontal brush spindles, which are insulated from the rocking bar by hard wood collars. Various other mechanical details are set forth in the drawings, but perhaps it should be mentioned that the radial lines round the outer edge of the armature in fig. 182 indicate the edges of the small pieces, *e e*, of the connectors.

FIG. 184.



This machine is shunt-wound, and, when driven at 680 revolutions per minute, develops an E.M.F. of 120 volts, its maximum output being 12,000 watts. The resistance of the armature when cold is 0·045 ohm and of the shunt coils 40·9 ohms.

The sectional area of the iron in the armature core is 58 sq. in., and the maximum magnetic induction through it is 20 Kapp lines, while the sectional area of each limb of the field-magnet is 67·5 sq. in. and the magnetic induction through them 12 Kapp lines.

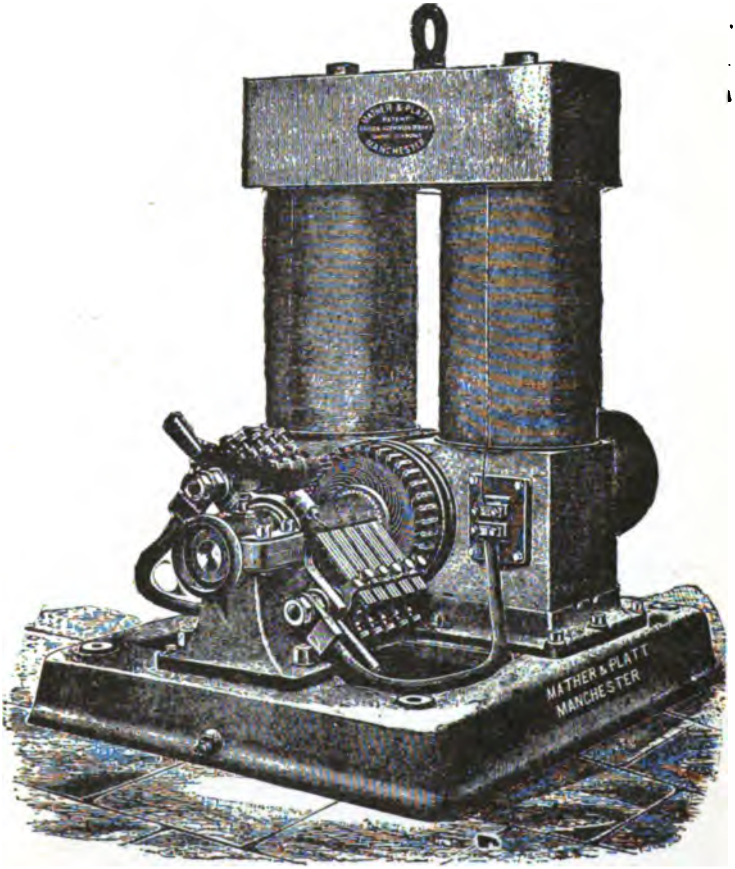
The unit of magnetic induction here referred to was introduced by Mr. Kapp, who considered it more suitable for practical purposes than that based on the C.G.S. system. One Kapp line is equal to 6,000 C.G.S. lines, and the unit of area is taken as the square inch instead of the square centimetre. This departure is, perhaps, in some respects, unfortunate; but the method will probably survive, as it is already used by the majority of English manufacturers. The conversion from one system to the other can, of course, be accomplished without much labour, remembering that one square inch contains about 6·45 square centimetres.

Therefore the magnetic induction through the armature core above referred to is about 18,600, and that through the field-magnet 11,100 C.G.S. units.

Many forms of dynamo machines have been introduced by Mr. Edison. In some of the earlier ones the field-magnets consisted of a number of straight electro-magnets of circular section, divided into two sets, terminating in a pair of massive pole-pieces, between which the armature revolved. This form of construction was essentially bad, on account of the large amount of wire required as compared with the mass of iron in the cores, for the most economical form in this respect is a single circular core.

Since the laws which govern dynamo construction have become better understood, Edison's field-magnets have, of course, been provided with single massive cores; but in England the great improvement made on the machine was due to Dr. Hopkinson, and in fig. 185 is illustrated the latest form of the 'Edison-Hopkinson' dynamo. It differs from the machines already described in that the armature is placed at the lower ends of the field-magnet cores, an arrangement which at one time was frequently employed, but which has the disadvantage that the iron bed-plate more or less magnetically short-circuits the pole-pieces, and affords a path through which some of the lines of force leak, instead of passing through the armature. On the other hand, there is the advantage that the centre of gravity of the moving parts is kept low, thus adding to the stability of the machine, and also in some cases affording facilities for driving direct from a steam-engine fixed upon the same bed-plate. In the machine under notice this leakage is

FIG. 185.



reduced by interposing a massive slab of zinc between the pole-pieces and bed-plate, as in fig. 185. We will endeavour presently to see to what extent this is successful.

Each of the circular field-magnet cores, together with its pole-piece, is a single forging of wrought-iron; the yoke is also of wrought-iron, rectangular in shape and very massive; it is secured to the cores by two bolts, and great care is taken to make the surfaces in contact fit truly, so as to avoid, as far as possible, the introduction of any magnetic resistance. The armature-shaft bearings are carried by short cast-iron standards bolted on to the bed-plate. The armature is drum-wound, and its core is built up of thin discs, insulated with paper, and threaded on to the steel shaft. Two thick stiff end-plates hold the core-discs in position, one bearing against a washer which is shrunk on to the shaft, while the other is driven up tight by a large nut. There are forty sections in the armature, each of one convolution, and the conductor consists of thick copper bars, the cross-connections being made with stiff copper strips. These strips, the outer set of which can be seen in the figure, are led round spirally to the segments of the 40-bar commutator in such a manner that a coil whose plane is vertical is connected to segments which lie near the horizontal, and, consequently, the diameter on which the brushes are set is nearly parallel, instead of at right angles, to the direction of the lines of force through the armature.

The machine illustrated is shunt-wound, the wire composing the field-magnet coils being rectangular in section, thus reducing the waste space between the adjacent convolutions. The terminals of the machine are fixed on the pole-cheeks, and the marked difference in the size of the massive conductor which carries the whole current from the brush-bar to the terminal, compared with the thinner shunt wire, will be observed. When driven at 475 revolutions per minute, this machine is capable of developing 52,500 watts (105 volts, 500 amperes), and on account of the extremely low resistance of the armature, it is practically self-regulating through a considerable range. Each brush is divided into five sections, all adjustable independently, and by this means a sufficiently large bearing surface upon the commutator is obtained without introducing any difficulty in compensating for unequal wear, such as would arise if one undivided brush were employed.

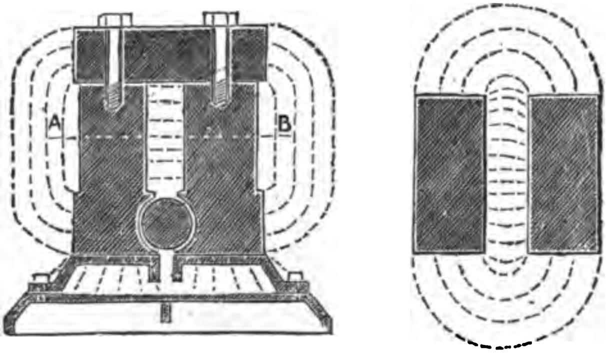
This type of dynamo is additionally interesting from the fact that it has been carefully studied and tested by the Drs. Hopkinson, the results having been published in various papers. The object was (*a*) to endeavour to gain such information as would enable the performance of a dynamo to be predicted, when its configuration and the various dimensions and qualities of the material employed (especially the iron) are known; and therefore (*b*) to enable any machine desired to give certain results at a certain speed, to be designed with the greatest accuracy.

We know that in every machine the magnetising force required to develop the field in which the armature rotates is always in excess of that usefully employed; or, in other words, more lines of force are generated than actually pass through the armature core, the difference being caused by leakage at various points.

We will briefly describe one portion of the experiments with the view of enabling the student to better judge of the amount and locality of such leakage in any given machine.

The portion of the experiments referred to consisted in the first place of determining exactly the ratio of lines of force actually generated, to the lines passing through the armature core. This ratio will of course always be greater than unity, and may be denoted by ν.

FIG. 186.



In fig. 186, a machine with rectangular cores is shown in section, and lines of force are sketched to roughly indicate the principal paths of the leakage. Some of the lines pass directly from one limb to the other, others leak out of the yoke to the pole-pieces, while many pass through the arched slabs of zinc (on which the pole-pieces rest), down into the iron bed-plate.

We have previously mentioned that it is possible to compare the number of lines of force cutting or cut by a coil of wire in two or more given fields, by placing a galvanometer in circuit with the coil and observing the deflections. As the resulting E.M.F. is usually comparatively low, the galvanometer must be a delicate one, and it is usual to employ one in which a short strongly magnetised needle is suspended by a silk fibre inside a coil of many turns, the deflections of the needle being made evident by the movement of a beam of light reflected on to a scale by a small mirror fixed to the magnet. But in such a test it is necessary that the needle shall not begin to move or change its position until the whole of the brief current has actually passed through the coil, and it is preferable to make the needle short and somewhat heavy, avoiding as far as possible the introduction of any damping effect. The number of divisions on the scale travelled over by the beam of light may then be taken as proportional to the E.M.F. developed, and therefore to the number of lines of force cut.

In the experiments under notice a current of 5·6 amperes was maintained through the field-magnet coils, from a battery, the armature being disconnected. A single convolution of wire was then wound round the middle of one limb as at B, the ends of this wire being joined to an instrument such as that just referred to, and known as a ballistic galvanometer. The needle being at rest, the field-magnet coils were short-circuited, thus suddenly stopping the current in them, and the lines of force, in collapsing, cut the single turn of wire and induced a current therein, which, passing through the galvanometer, deflected the beam of light for a moment. The needle having again settled itself steadily at zero, the short-circuiting connection was removed, thus once more suddenly passing the current through the magnet coils. The lines of force in springing outwards again cut the single coil, inducing a current which deflected the needle to an almost equal extent, but in the opposite direction to that produced by the first current. In this case the mean of the two deflections was 264 divisions, which, neglecting the small amount of residual magnetism, may be taken as proportional to the induction in, or the number of lines of force passing through, the field-magnet limb. The next step was to determine what proportion of these lines passed through the armature, which was of the drum type, each coil consisting of one convolution only.

The wires leading from the galvanometer were soldered one to each of two adjacent commutator bars, and the armature placed so that the plane of the coil connected to those bars lay at right angles to the lines of force.

The field-magnets were excited as before by a current of 5·6 amperes, and the deflection noticed first when the current in them was stopped by short-circuiting, and again when the current was sent round them a second time, so as to suddenly withdraw lines of force from, and then to thrust them through the armature core. The mean of these two deflections was 200 divisions, and therefore

$$\frac{\text{Induction through field-magnets}}{\text{Induction through armature}} = \frac{264}{200} = 1 \cdot 32 = \nu.$$

That is to say, 24·24 per cent. of the total number of lines of force generated failed to reach the armature core owing to leakage. Although this method does not give us the actual number of lines of force in C.G.S. units, it nevertheless gives the proportion correctly, and in these experiments the number passing through the armature was estimated in C.G.S. units by running the machine at a known speed and measuring the resulting E.M.F. without allowing a current to pass through the armature and distort the field. Then the actual number of lines in any other part of the magnetic circuit could be found by simple proportion. Having shown that 24·24 per cent. of the lines of force were lost by leakage, the next step was to localise that leakage, that is, to discover at what points it occurred. This time the galvanometer, being less sensitively adjusted, gave a mean deflection of 115 divisions with one turn round the middle of one limb, when a current of 5·6 amperes through the field-magnets was suddenly started and stopped as before. Four convolutions were then wound round the bed-plate directly under the armature shaft, and, the current being stopped and started in the field-magnets, the galvanometer indicated a mean deflection of 50·25 divisions, due to the lines of force which leaked through the bed-plate and cut the four convolutions wound round it. Four turns were employed in order to get a fairly high deflection. The induced E.M.F. being, however, four times that which would be obtained with one turn, it becomes necessary, to enable this result to be compared with the previous one, to reduce it to the value of one convolution, thus :

$$50{\cdot}25 = 12{\cdot}6 \text{ divisions, nearly.}$$

The leakage through the space between the field-magnet limbs was measured with a coil of ten turns wound on a square frame, and by a similar calculation was found to be proportional to eight divisions with one convolution.

The horns of the opposite pole-pieces approach each other both above and below the armature to within 12·7 centimetres, the depth of each being 8 centimetres. The leakage across each of these gaps was found to be 1·6 divisions, or 3·2 divisions for the two. Reducing these losses to percentages of the total induction, we have

The leakage through the zinc plate and iron base	= 10·3	per cent.
The gaps between the horns account for	2·8	,,
And the area between the limbs . .	7·0	,,
Making a total loss accounted for .	20·1	,,
Out of an observed loss of . . .	24·24	,,

The leakage through the shaft and from pole-piece to yoke, and one pole-piece to the other by exterior lines will account for the remainder.

This ratio, *r*, will, of course, vary slightly with different exciting currents in the field-magnet coils, especially when the iron approaches the saturation point, because, the permeability of the iron decreasing with the induction through it, while that of the air remains constant, the proportion of leakage will be greater.

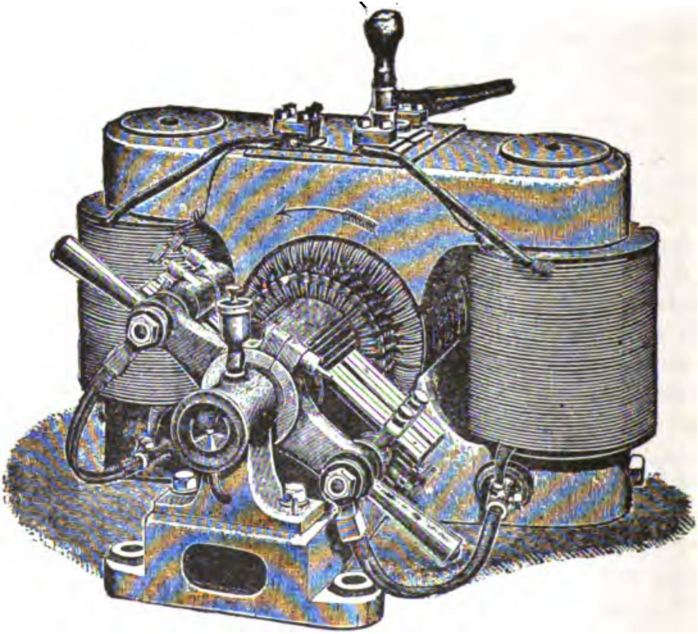
These experiments constituted the first definite attempt to discover the extent and the locality of the leakage of lines of force generated by the current in the field-magnet coils, and it will be seen that almost a quarter of the power spent for the purpose of developing the field in this particular case was wasted. The large proportion of the leakage for which the bed-plate accounts shows the great advantage pertaining to the inverted horse-shoe form of field-magnet. It is to be regretted that the other types of field-magnet which are now extensively employed have not been subjected to similar experimental examination, but a study of these experiments, together with those made in connection with the machine next to be described, should enable the student to make a very fair estimation in any ordinary case.

It would, for instance, be safe to predict that for a given magnetic saturation of the iron, comparatively little magnetic leakage would take place with the machine depicted in fig. 175, for the brackets are made of gun-metal, and, excepting the shaft, there is practically no magnetic metal employed which would tend to increase the leakage. In this respect this machine is probably the best of any we are acquainted with; but we may again remark that the amount of leakage also depends largely upon the degree of saturation of the iron, and upon the magnetic resistance of the whole magnetic circuit. On the other hand, it would be false economy to make the leakage extremely low, if the extra expense incurred in so doing were out of proportion to the cost of the power which would otherwise be wasted in the generation of the field.

The 'Manchester' dynamo, made by Messrs. Mather & Platt, is illustrated in fig. 187. The arrangement of the field-magnets differs somewhat from that in the machines hitherto described. Two electro-magnets are fixed vertically with their like poles uppermost, the similar poles being in each case joined together by massive iron yokes, shaped as shown, so as to form the pole-pieces between which the armature rotates. The lines of force due to the field-magnet coils are thereby provided with an easy path for completing their respective circuits, and an intense field, is projected through the armature. The vertical members of the field-magnets are of wrought-iron, let into the horizontal yokes, which, being of cast-iron, have about twice the sectional area of the cores. The lower casting is extended on both sides so as to form the bed-plate of the machine, and the centre of gravity of the moving parts being low, it is comparatively easy to rigidly fix the machine in order to obtain great steadiness in running.

The shaft carrying the armature is made of Bessemer steel, the bearings being of gun-metal, and a free space along the shaft is provided to admit air for ventilating the armature. When driven at 1,100 revolutions per minute, the machine illustrated, which is compound-wound to maintain a potential difference of 100 volts, is capable of generating a current of 80 amperes or a maximum output of 8,000 watts.

FIG. 187.



The commutator in all dynamos of this type consists of forty bars of hard-drawn copper insulated with mica. Each arm of the rocking-bar carries two brushes, each brush being independently adjustable for the reasons already explained. The diameter of commutation with machines of this class, in which the direction of the lines of force through the armature is vertical, approximates to the horizontal, and this position in the Manchester machine is more nearly approached in consequence of a peculiarity in the curvature of the pole pieces. Instead of the polar surfaces being made concentric with the armature, they are struck from a radius greater than that from the centre of the shaft, so that the pole-pieces are brought slightly nearer the armature at points opposite the extremities of its vertical diameter. The lines of force are therefore more concentrated at these places, which reduces the distortion, and, increasing the activity of the most active or vertical coils, decreases that of those near the neutral point.

The armature is of the ring type, the core consisting of the usual thin iron discs clamped between the ends of a gun-metal frame. The arms of this frame, which fit into slots in the discs, are free of the shaft, so that a clear space for ventilation is retained. The end-plate nearest the commutator is keyed to the shaft, while the other is held up tight against the plates by means of a nut. The wire is wound in forty pairs of coils, the resistance from brush to brush being 0·084 ohm.

The shunt coils on the field magnet have a resistance of 41·5 ohms, and the series coils, which are wound outside the shunt coils, have a resistance of 0·049 ohm.

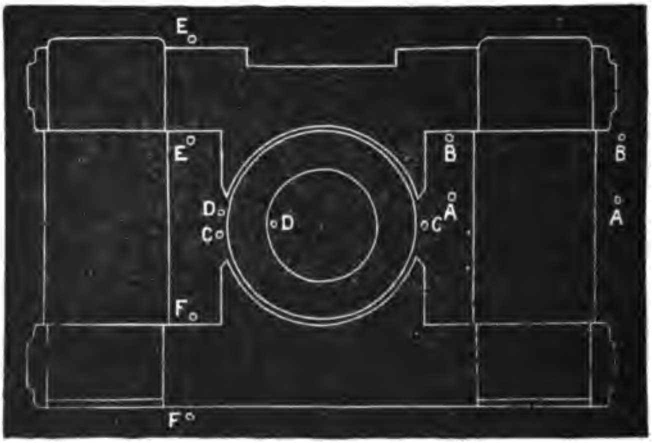
The gross weight of the machine is $10\frac{3}{4}$ cwt.

The brothers Hopkinson also made on this machine some experiments similar to those already described, and we may briefly refer to the simpler of the experiments which show the percentage and the locality of the leakage of the lines of force. Fig. 188 gives an outline of the machine, and shows the various positions of the testing-coils. As in the other experiments, the armature was disconnected, and a constant current obtained from an independent source to magnetise the field-magnets, the lines of force being made to cut the testing-coil by suddenly starting and stopping the current in the field-magnets, and the mean of the two observed deflections of the ballistic galvanometer calculated as before. In the first experiment four turns were taken round the middle of one limb at A A, and the mean deflection was observed to be 214 divisions. But as with a single turn of wire only one-fourth of this would have been obtained, $\frac{214}{4} = 53·5$ represents the total induction through the field-magnet core in terms of the arbitrary unit here assumed. But an equal number of lines pass through the other vertical limb ; therefore, the total induction through the field-magnet cores, as shown by this first measurement, may be represented by 107.

The coil was then raised to B B, where the mean deflection was 206, or, for a single turn, $\frac{206}{4} = 51{\cdot}5$, or 103 for the two limbs, and the mean of these two results—viz. 105—was taken as the mean induction in the field-magnet cores.

Three turns were wound round the armature at C C, where the deflection obtained was 222 divisions, or, for one turn only, $\frac{222}{3} = 74$, which represents the total induction through the space occupied by the armature. But we know that in a Gramme ring a certain number of lines pass diametrically across instead of round the armature core, which number becomes greater when the iron is so saturated that its permeability is low—perhaps lower even than that of the shaft—and the next experiment sought to determine the waste due to this cause. Four turns were taken round D D, the deflection being 141, or 35·25 in terms of one con-

FIG. 188.



volution. But as an equal number of lines pass through the other half of the ring, we must double this, getting 70·5 as the effective induction through the core, against 74 through the whole armature space and 105 through the field-magnets.

At E E 39·75 divisions due to one convolution were obtained, and the induction being the same on the other side, the total induction = 79·5.

At F F the result was higher, being 41·75, or 83·5 for both sides, the difference being caused by the easier path at the bottom of the machine offered by the bed-plate and bearings, and, of course, these additional lines are wasted.

We see, therefore, that in this case a large number of the lines of force generated are wasted; in fact, here

$$r = \frac{\text{lines through field-magnets}}{\text{lines through armature core}} = \frac{105}{70{\cdot}5} = 1{\cdot}49 \text{ nearly.}$$

This loss is partly accounted for by the extension of the lower yoke-piece to form the bed-plate and the use of iron supports for the bearings, and is, no doubt, fully compensated for by advantages from a mechanical point of view. But it will be observed that almost 5 per cent. of the lines passing through the armature leave the core and pass diametrically across the ring; this large proportion is, in a great measure, due to the fact that induction through the armature core was very high, viz. 20,000 C.G.S. units.

Another form of double horse-shoe magnet machine, and one which differs considerably from any yet described in several important mechanical and electrical details, is that constructed by Messrs. Laurence, Paris, & Scott, and illustrated in fig. 189, a section through the machine being also shown in fig. 190. The field-magnets are of cast-iron, made in two parts firmly bolted together and provided with flanges to hold the four exciting coils, the lower casting having additional flanges to receive the foundation bolts. The armature shaft is supported by cast-iron brackets provided with gun-metal bushes and bolted to projections from the lower pole-piece. The pole-pieces are bored out circular to form the armature space. The armature is drum wound, but is furnished with teeth projecting between each of the sections, as in one of the earliest forms of armature devised by Pacinotti, whence these projections are known as Pacinotti teeth.

The chief objection to this type of armature core is, that

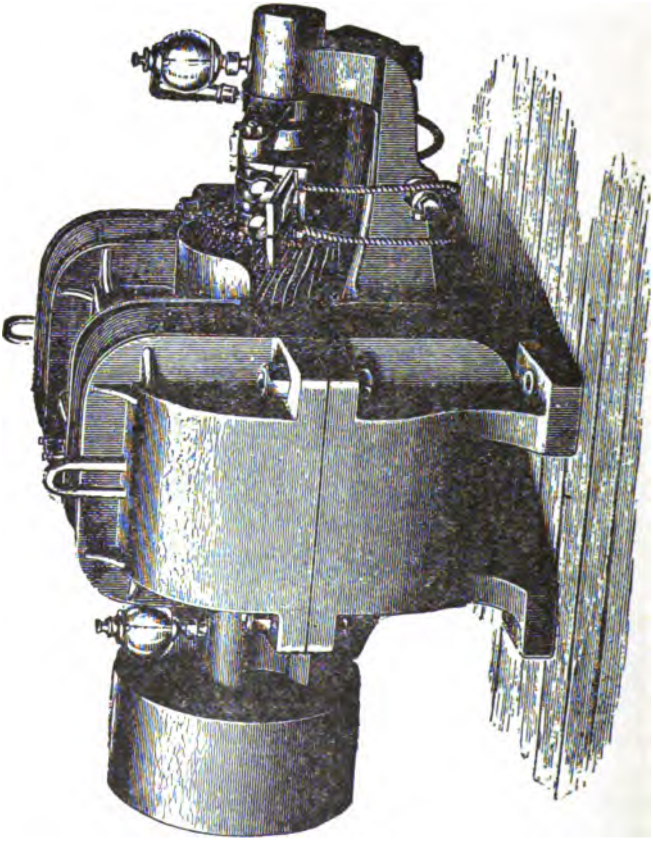
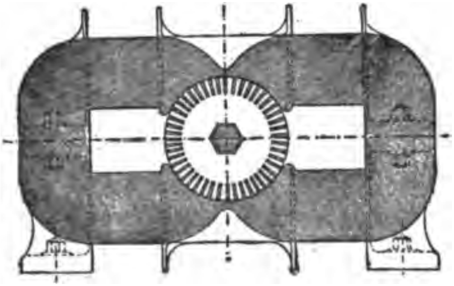


FIG. 18

although some of the iron is brought nearer the field-magnet poles, its uneven surface perturbs the magnetic field, keeping it in a state of oscillation, and setting up eddy currents in the field-magnet poles. But in the machine under notice this effect is almost entirely obviated by employing a large number of teeth and making the distance between them very small, so that the oscillation of the field is very slight—indeed, practically imperceptible. One section of the armature is wound in each slot, which is just wide enough to take a single insulated wire, and deep enough to hold the number of wires in each section.

In the armature shown in fig. 190 each section consists of six convolutions, so that there are six wires in each slot If the slots were made too deep, some of the lines of force would not be cut by the inner wires; in the present case, the number thus missed is very small, practically none being lost in armatures having but two turns in each section. The core is built up of thin discs of soft iron, of the shape shown in the sectional figure. The

FIG. 190.



centre holes are hexagonal, and the plates or discs are threaded on to the hexagonal steel shaft, so that each one is driven direct from it. This, added to the fact already mentioned, that the wire is wound in deep and narrow slots, makes the armature as a whole mechanically strong, there being little risk of a sudden stress shifting the core or stripping the conductor from its place. There is an unusually large proportion of iron in the core; in fact, the whole of the space, except the small amount taken up by the insulating material, is occupied by the iron plates and steel shaft, no allowance whatever being made for ventilation It will be observed, however, that a large amount of the iron core (the edges of the teeth) is in direct contact with the air, and as the armature rotates the heat is carried off by convection, thus preventing any great rise in temperature. The facility afforded in this way for the dissipation of the heat generated in the core, gives to the Pacinotti ring one very important advantage. The commutator sections or bars are insulated with mica, rings of asbestos and fibre being employed at the ends of the bars to insulate them from the clamping-nut and washer by which they are held in position.

When the machine is compound wound, the series turns are usually wound on the top magnet cores. Should the series coil not occupy the whole of the wire-space, it is filled up with a portion of the shunt wire, which also occupies the whole of the space on the lower magnet cores.

For large machines, sheet copper, insulated with strips of calico, is used for the series winding.

The following details concerning one of these machines, very recently constructed to give 12,000 watts at an E.M.F. of 100 volts when driven at 710 revolutions, will be of service.

The armature is wound in fifty-two sections, each of two convolutions, so that there are fifty-two bars in the commutator and two wires in each slot. The sectional area of the cast-iron field-magnet cores is considerably greater than that of the armature core, the former being 98 and the latter 29·7 square inches. The maximum magnetic induction through the armature core is nearly 23 Kapp lines per square inch, or about 21,000 C.G.S. lines per square centimetre.

The armature conductor is of braided wire, very carefully insulated from the core and from the adjacent wire in the same slot, and the current density in the conductor, with 120 amperes, is 3,210 amperes per square inch.

The series winding on each of the top limbs consists of twenty-eight turns of sheet copper, 4·5 inches wide and 0·025 inch thick, having a resistance of 0·0124$^{\omega}$, and giving, with the maximum current, 3,360 ampere turns.

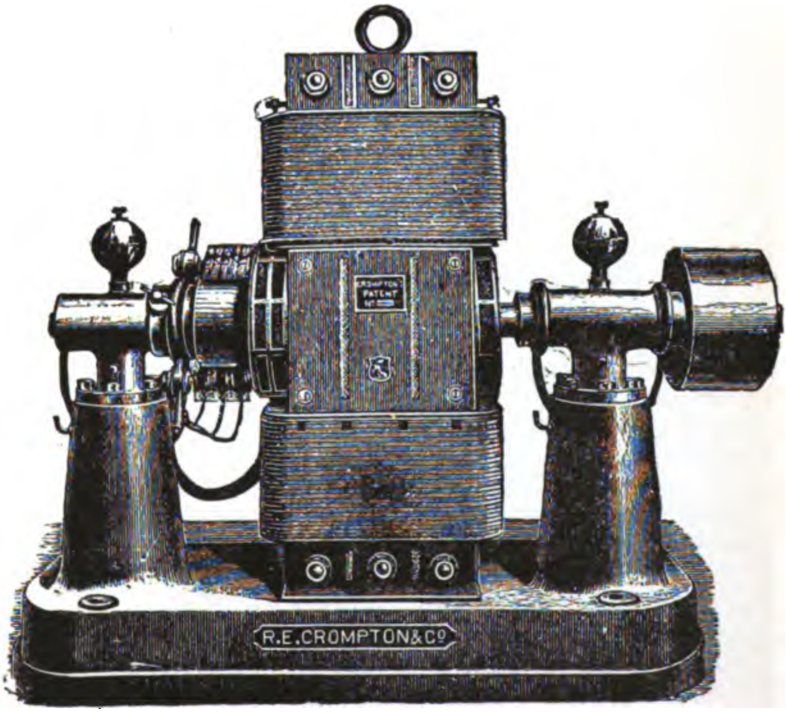
The resistance of the shunt coils is 32·4$^{\omega}$, the ampere-turns, with the potential difference of 100 volts, being 6,468.

We may from the above easily determine the number of watts expended in the various parts of the circuit, remembering that the amount developed in the external circuit when the maximum current is being obtained will be EC = 100 × 120 = 12,000 watts. Thus,

Shunt coils	$32{\cdot}4^{\omega}$,	watts lost with	100 volts		= 308
Series ,,	$0{\cdot}0124^{\omega}$,	,, ,,	120 amperes		= 178
Armature ,,	$0{\cdot}045^{\omega}$,	,, ,,	120	,,	= 648

Fig. 191 illustrates the 'Trade' dynamo of Messrs. Crompton & Co. It is somewhat similar to the Manchester dynamo, and to

FIG. 191.



that just described, in that it consists of a double electro-magnet, the difference being that it is fixed vertically instead of horizontally. The field-magnet cores are of annealed wrought-iron, and are fixed by bolts and nuts to the cast iron bed-plates. The coils are wound on four bobbins, and connected in such a manner that the two coils on the same magnet limb have their similar poles adjacent, the pair on the one side having their north poles and that on the other side their south poles adjacent, so that the lines of force pass horizontally through the armature from and into those portions of the vertical limbs between the coils, which portions therefore form the pole-pieces.

This machine is furnished with a ring armature, in which the iron discs are insulated by varnished paper, the built-up core being dried in an oven before the conductor is wound over it. The steel shaft has four longitudinal grooves, into which fit radial bars of aluminium bronze, their length along the shaft being equal to the length of the core. The outer ends of these bars dovetail into notches in the discs. The conductor is of rectangular cotton-covered wire, wound in one layer on the outer circumference, but in two layers over the inner face of the core, which, besides being smaller, is partly occupied by the radial driving bars. Insulated steel wedges project at intervals from the core, to drive the conductor on the outer circumference, and the armature is also bound over with thin tinned steel wire to prevent bulging. The brushes are of stencil copper, carried on a gun-metal spindle which is insulated by a fibre collar from the cast-iron rocking-bar.

We have remarked that it is not possible in practice to 'compound' a machine to give a constant current, in the same manner that a constant potential can be maintained. Hence a variety of other devices, mostly mechanical, have been suggested for the purpose, one of which has already been described, and we will now direct attention to a machine designed and constructed by Mr. J. G. Statter, to maintain a constant current at a constant speed when the external resistance is varied; or when the speed is varied and the resistance remains unaltered; or within certain limits when both speed and resistance vary.

When an armature is rotated in a simple field, with the brushes removed from the commutator, there are two points, at opposite extremities of a diameter, at one of which the potential is a maximum (positive), and at the other a minimum (negative), and it is at these points that the brushes should be set in order to obtain the greatest difference of potential. From the negative to the positive brush either way round the commutator, the potential gradually increases in value, and if the negative brush were shifted, say, 20° forward, it would touch at a point of higher potential, and consequently the *difference* between the two brushes would be reduced. A like reduction would follow if the positive brush were moved forward, because it would then make contact at a point of lower potential; and in the third case the difference of potential between the two might be decreased by giving them simultaneously a greater angle of lead, until they would be at nearly the same potential when moved through an angle of 90°.

It follows that by merely shifting the brushes the potential difference at the terminals may be made what we please from the maximum downwards, and this method might be employed to vary the pressure, and therefore the current, to suit the requirements of the circuit. Thus the brushes might be set 20° ahead of their normal position of no sparking—that is, where the difference of potential between them is at a maximum—and then, if the current became too strong, the brushes could be shifted yet further ahead, thus reducing the potential difference and also the current; while by moving the brushes back towards their normal position, the current could be increased in strength, should it fall below the desired value.

This would, however, be impracticable in an ordinary dynamo, on account of the terrific sparking which would ensue; and one of the principal features in Mr. Statter's machine is the method by which he renders it possible to vary the lead of the brushes through a considerable angle, without causing this sparking.

Confining our attention at present to the case of ring armatures, it will be remembered that when a coil which is carrying the whole of the current generated in one half of the armature is short-circuited by the brush, the electro-magnetic inertia of the coil, due to its self-induction, prevents the instantaneous cessation of the current; and that even if the coil is commutated at the moment when its plane is exactly at right angles to the field and therefore in itself inactive, yet there will be a considerable spark caused by what we may term the self-induction current in the coil. For this reason it is found to be necessary to give the brushes a slight extra lead so that the coil may begin to cut lines of force, and have induced in it an opposing E.M.F. sufficiently strong to just counteract this self-induction effect, and stop the current in the coil before the brush leaves its commutator bars. Now the weaker the field the greater is the extra lead required to obtain this opposing E.M.F. The extra lead also increases with the self-induction of each individual coil, while in the case of some armatures, having but one or two convolutions in each section, it is practically *nil.*

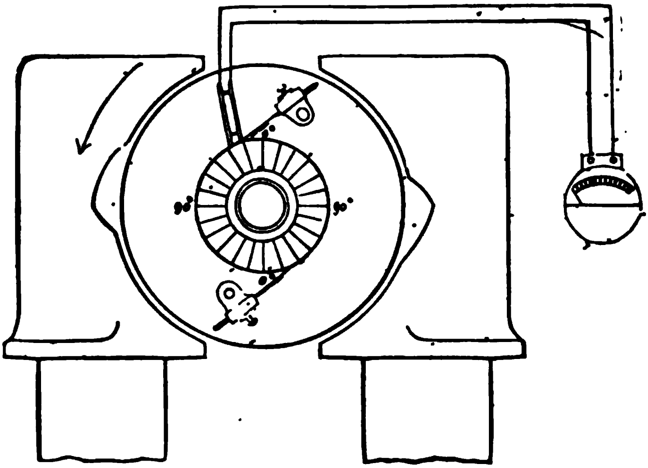
It must be remembered that this *extra* lead is not due to the distortion of the field, but is simply required to prevent the spark which would otherwise result from the self-induction of the coils. Neither must it be forgotten that if the current is kept constant in strength, the E.M.F. thus required to be counterbalanced is the same whether the coil is short-circuited at 10°, 20°, or 30° ahead of the normal position. In an ordinary field the activity of the coil increases with such rapidity as it leaves the neutral position, that the self-inductive effect is more than balanced, and there is a remaining E.M.F. opposite in direction induced by the field on the coil, which is then competent to cause sparking.

But if the field were made uniform and of such strength that for a certain distance beyond the neutral point—say through an angle of 40°—the number of lines cut by the coil at any position in that angular space was just sufficient to counterbalance the E.M.F. of self-induction, then the potential difference at the ends of the coil throughout that range would be *nil*, and no sparking would ensue if it were short-circuited.

This is Mr. Statter's method; and in order to allow a strong field to be employed, each coil contains an unusually large number of convolutions, there being also plenty of iron in the armature, so that a strong field is required to counterbalance the resulting high self-inductive effect. Portions of the pole-pieces are cut away at such points as will make the density of the lines of force entering the armature over a given angle equal; and the exact places where the field has to be increased or reduced in strength are ascertained by experimenting in the following manner.

A series machine is constructed in the ordinary way, having pole-faces concentric with the armature, but with a rather larger number of convolutions than usual in each armature section. The speed at which it is driven is kept constant, and also the current, say at 10 amperes, when the effect of self-induction, which has to be balanced, but not over-balanced, will be constant also. The first step is to find out what is the activity of a single coil at the various stages of its circular path, and, in order to decide this, use is made of a set of apparatus which has been employed for different objects by other experimenters with good results. It consists of a voltmeter of the requisite range, having its terminals attached by flexible wires to two copper strips, which are fixed at a sufficient distance apart by pieces of insulating material, so that their ends bridge over the width of a commutator segment. The arrangement of this simple apparatus and the method of using it are indicated in fig. 192. While the machine is running, and sending a current through an external resistance, the exploring brushes, as we may term them, are held against the commutator, as indicated in the figure, and each coil as it passes the point where the brushes are placed is connected up for a moment to the voltmeter, which indicates the electromotive force developed in the coils while passing that position. The exploring brushes are shifted by suitable stages round the whole of the commutator, and

FIG. 192.



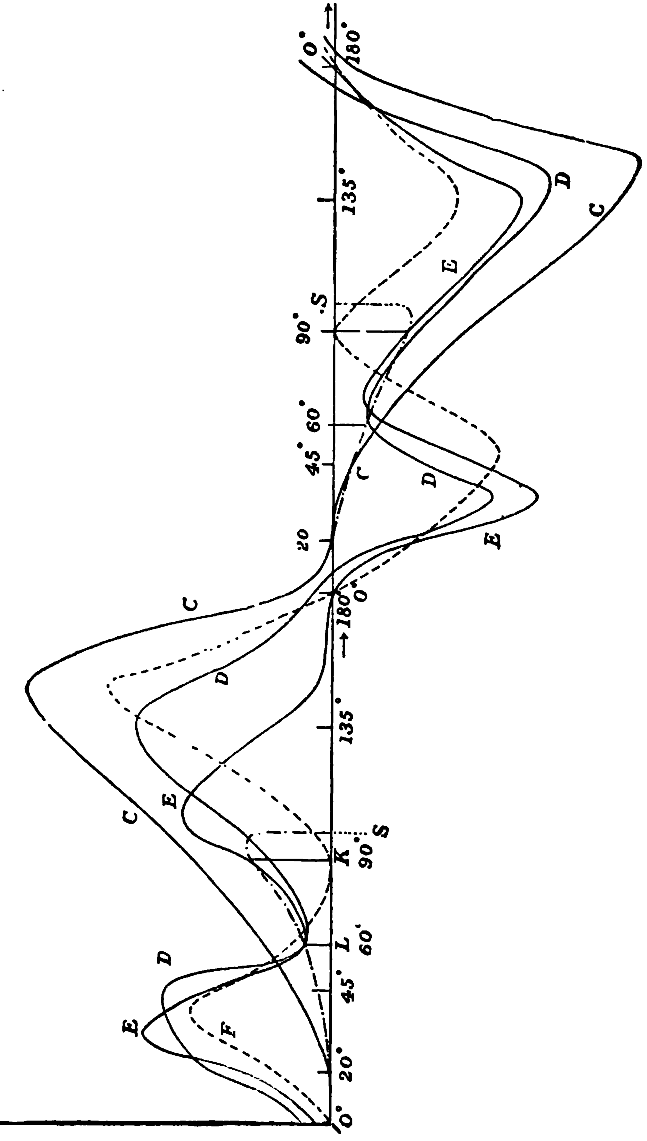


FIG. 193.

the deflection of the voltmeter noted for each position. The results are plotted in the form of a curve (see fig. 193), the distances along the horizontal line being taken to represent the angular distance of the coil from the zero position on the commutator, while the vertical distances represent the E.M.F. in volts developed by one coil in the various positions.

The curve C C was obtained in this manner when the main brushes were placed in the normal position, the lead being about 20° The results obtained in passing *down* the commutator in the direction of rotation are plotted above, while those obtained in passing *up* are plotted below the line; and it will be observed that the E.M.F. at the extremities of each coil becomes *nil* at 20° from zero, while it is a maximum at about 150° from zero.

To facilitate comparison, both the point vertically above and that vertically below the centre of the shaft are regarded as zero points.

This curve having been obtained, the brushes were shifted forward to a position 60° from zero, and, regardless of sparking, the potential difference at the extremities of a coil in all the various positions was again measured. Another curve, D D D, was obtained by plotting these results, and it will be observed that, at the moment a coil is passing under the main brushes, the potential difference at its ends is considerable. This potential difference, which gives rise to the sparking, is in fact proportional to the height of the ordinate L, and it is equal to the excess of the E.M.F. induced in the coil by the powerful field at this point over that momentary E.M.F. due to the self-induction of the coil at the moment it is short-circuited. It is clear, then, that to eliminate the sparking when the main brushes are given a forward lead of 60°, the strength of the field must be reduced by just so many lines of force as would develop an E.M.F. proportional to the ordinate L, and then the E.M.F. of self-induction and that being induced in the coil would exactly balance. The length and number of active conductors in each coil, and also the speed of rotation being known, this number of lines of force can readily be determined.

The main brushes were next given a lead of 90°, when, as might be expected, the sparking became even more severe, but by means of the exploring brushes and voltmeter the curve E E E was rapidly obtained. The E.M.F. in excess, which at this position of the brushes causes the sparking, is represented by the ordinate X, which gives a means of estimating the extent to which it is here necessary to reduce the strength of the field. About ten such curves were obtained with the brushes in various positions between 20° and 100°; but we have only given three of them in order to avoid a complex figure. From each point on the horizontal line corresponding to the angular distance of the main brushes from zero, a perpendicular is erected to cut the curve which was obtained with those brushes in that particular position (as we have observed, L and K are such ordinates), and by joining the tops of the whole of the ten ordinates the dotted curves starting at 20° and terminating at S are obtained.

The area contained between one of these curves and the horizontal line affords an indication of the amount of iron which should be removed from the corresponding pole-face in order to weaken the field to the desired extent.

But since the very act of increasing the distance between the pole-face and the armature core at one point increases the density of the lines of force at another adjacent point, the areas only approximately represent the shape of the cavity required in the pole-face. For this reason the curves are, in practice, simply used as a guide to indicate to what extent the field requires reduction at the various parts, and the iron is removed to a rather less extent than is sufficient, so as to allow a margin for any error. Other curves are then obtained by means of the exploring apparatus, and a second approximation to the final result is arrived at, the process being again repeated if necessary. The dotted curve F was obtained with the brushes at 90° after the pole-face had been shaped, and shows by its coincidence with the horizontal line at 90° that no sparking took place with the brushes in that position.

One method of modifying the field is to cut a groove in the pole-face parallel to the shaft, after the manner shown in fig. 192, and it will be seen that the outline of the groove approximates somewhat to the dotted shaping curves in fig. 193.

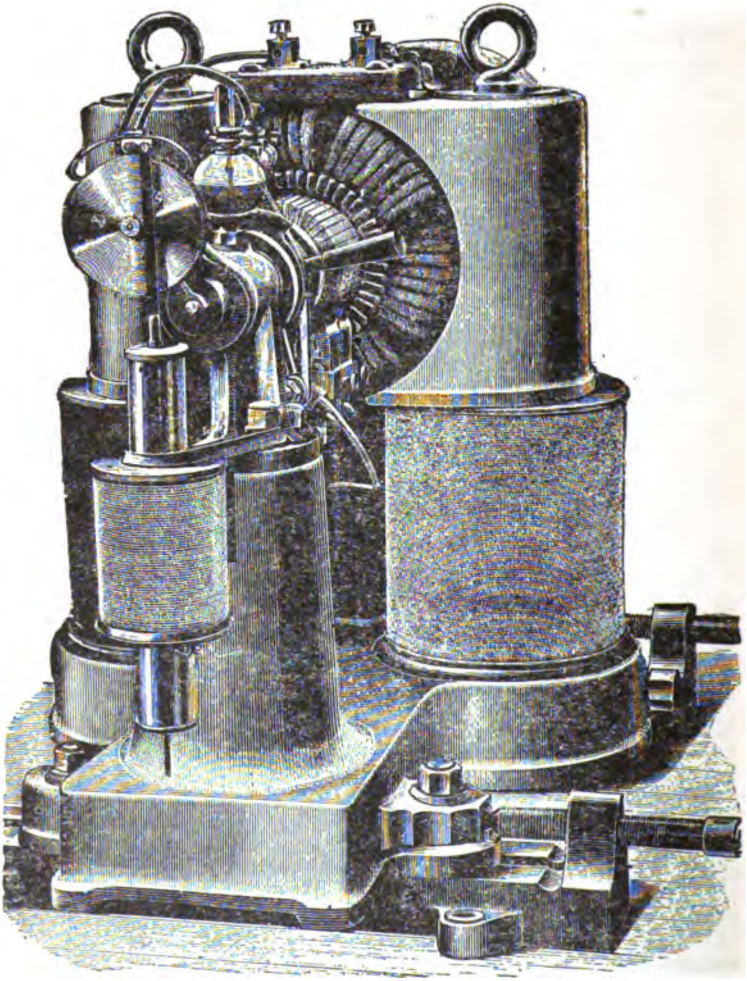
The desired result may, however, be obtained by removing the iron in a variety of ways, such as boring holes in the pole-pieces, or even by using iron of different permeability.

We have here considered the case of a ring armature machine, in which the maximum number of lines which each coil can at any one time embrace is only half the total number passing through the core. But in the case of a drum armature the whole of the lines can at once be embraced and cut by a coil during half a revolution; it is therefore only necessary to 'explore' through 180° round the commutator, and plot the curves, say above the line, to obtain one shaping curve. This will indicate approximately the amount by which the whole field must be reduced, and the whole of the iron may be removed from one pole-piece, or half from each, as in fig. 192.

In this manner, then, is it rendered possible for the brushes to be shifted through a considerable angle in order to vary the potential difference, and consequently the current strength, without introducing sparking. It now remains to show the method by which the brushes are automatically moved to the proper position when the current varies. A view of the machine, with its automatic regulator, is given in fig. 194. In this particular case, two deep grooves are cut in each pole-face, but they do not extend to the pole-cheek, so that, in external appearance, it is similar to an ordinary machine. The solenoid shown in the front of the figure is wound with thick wire, and is joined up in the main circuit, so that the whole current passes through it. Inside it is a core capable of a small vertical movement, its centre being below that of the solenoid. When the main current rises above its proper value, this core is sucked up, and throws into gear a simple mechanism which increases the lead of the brushes and so reduces the current; similarly, a reduction in the current strength allows the core to fall, when the mechanism is reversed, and the brushes recede towards the zero or maximum potential position.

The bar which carries the brush-holders is placed, as usual, on the end of the bearing next the commutator, the collar, however, being adjusted and the bearing oiled so that the bar can rock easily. On the upper part of the collar is fixed a toothed segment, which gears with a pinion on a spindle parallel to the main shaft; the other end of this spindle carries two ratchet-wheels, each $5\frac{1}{2}$ inches in diameter, but with their teeth set in opposite directions. The nearer of these ratchet-wheels can be seen in the figure; the other is but $\frac{1}{8}$ inch behind it, and the two are rigidly fixed together by means of three set screws. When

FIG. 194.



these wheels are rotated, the pinion at the other end of the spindle on which they are fixed communicates the motion to the toothed segment on the brush-bar collar, and so slightly alters the lead of the brushes, either forward or backward, according to the direction in which the ratchet-wheels are turned.

Above the wheels is a curved bar, with a pawl at either end, which, however, are not in line, one being placed directly over and gearing with the front wheel, while the other gears with the back wheel. When the machine is running, the curved bar has given to it a continual rocking motion through a small angle, by means of a rod having at one end a slot, in which plays a pin eccentrically fixed on the end of the main shaft. In the normal state, the range through which the bar moves is such that neither pawl quite touches the ratchet-wheel directly under it, but, by tilting the bar a little one way or the other, either pawl can be lowered sufficiently to gear with its wheel at every pulsation.

This tilting is given in the proper direction by the movement of the core in the solenoid, the core being attached to the curved rocking bar by a light rod, and, when the current becomes too strong and the core is sucked upwards, that pawl is thrown into gear which, step by step, gives to the brushes a forward movement, and *vice versâ.*

The large tube which, in the figure, can be seen passing right through the solenoid is rigidly fixed to it, and, in fact, forms the tube of the bobbin on which the wire is wound. It is made of brass, and inside it the core, which is a wrought-iron tube 1½ in. in diameter, slides freely. The solenoid is 6 inches in length, and the iron core is a trifle longer, its centre being about 1 inch below the centre of the solenoid. Its play is limited to $\frac{3}{16}$ inch, so that it can only move just far enough to throw the pawls in gear.

The machine regulates remarkably well under the varying conditions previously referred to, the brushes steadily travelling backward and forward with but little sparking. The machine pictured in fig. 194 was designed to supply a constant current of 10 amperes to a number of arc lamps joined up in series, and is driven at 1,000 revolutions per minute. Any alteration in the number of lamps in circuit of course varies the external resistance, and the regulator immediately moves the brushes to compensate for this. With the maximum number of lamps joined up, the potential difference at the terminals is 1,290 volts, so that the power available in the external circuit is 12,900 watts. It is series wound, the resistances, measured when the wires were hot, being: armature, 8·79 ohms; field-magnets, 3·3 ohms; regulating solenoid, 0·57 ohm. There are sixty commutator bars, and the number of convolutions in each section of the armature is fifty-four. The magnetic induction through the armature is 17 Kapp lines, or rather over 17,000 C.G.S. lines.

An interesting machine of this class is in use for generating the current for the Northfleet Tramway, where the motors on the various cars are placed in series, and the power required varies rapidly and considerably, while the current must be kept constant at 50 amperes. The maximum E.M.F. at the terminals is 450 volts, and the brushes are continually travelling backwards and forwards, the sparking being hardly noticeable.

Another type of dynamo, manufactured by the same firm, is illustrated in section in fig. 195, the section being taken vertically through the spindle. The machine is designed to be driven direct by a steam-engine, which is built upon the same bed-plate with it, and it is, consequently, calculated to develop the requisite E.M.F. at a low speed.

The framework is a hollow casting, well stayed with cross-ribs, and cast solid at one part to form the yoke. The slabs forming the limbs of the field-magnet are of wrought-iron, of the brand known as 'Kirkstall scrap,' carefully annealed, each finished limb weighing 8 cwt.; they are fixed on to the framework by two bolts passing horizontally through the solid part of the casting.

The armature is drum wound, having Pacinotti teeth, the core being made of thin discs of Swedish iron, punched out to the required shape, and effectually insulated one from another by thin asbestos tissue and shellac varnish.

A number of keyways are planed in the shaft, and corresponding horns or projections are stamped out on the inner edges of the discs, to fit accurately into these keyways, the shaft being also fluted between them so as to afford air-passages under the discs.

To form the Pacinotti teeth, the outer periphery of each disc is punched symmetrically with respect to the inner horns, so that, when the discs are threaded on to the shaft, rectangular grooves

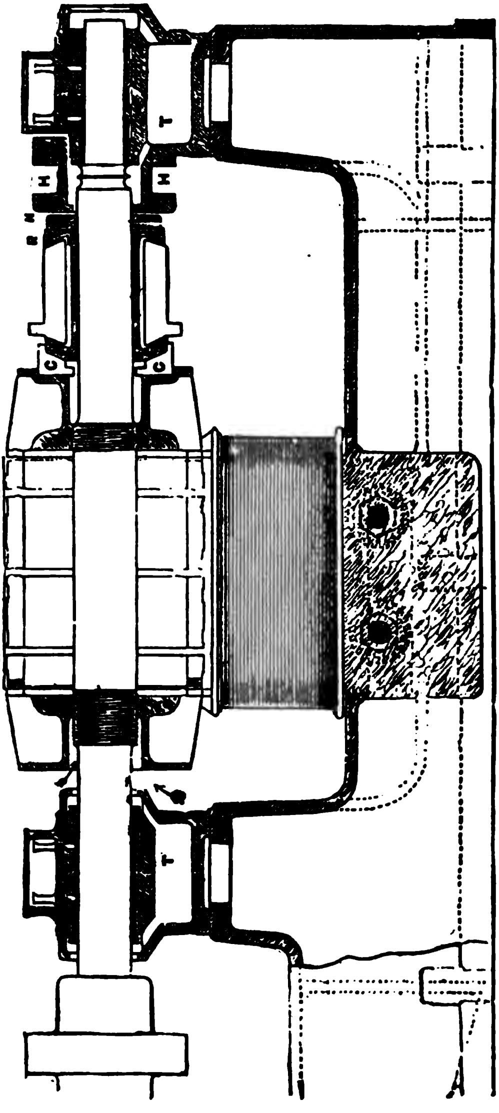


FIG. 195.

(with the greater dimension radial) are formed along the surface of the core, and in these grooves is placed the conductor.

The method of insulating the wire from the core is very effectual and somewhat unique. Strips of mica are placed in the grooves referred to, and cemented together so as to form a continuous trough. In addition to this the conductor is provided with a double covering of cotton, and a serving of silk at the angles where it is bent round the edges of the core. In threading the discs upon the spindle, three spaces, *a a a*, are left between them. Fan-blades are set in these spaces, and the whole of the plates are clamped together by the cast-iron end-plates, A and B, which are screwed upon the shaft. Underneath the plate A, at the end remote from the commutator, are little air-passages communicating with the flutings, previously referred to, in the shaft; and when the armature is rotated, air is drawn in as indicated by the arrows under the end-plate, and along the flutings under the edges of the discs, and is forced out at *a a a* by the fan-blades, thus giving most efficient ventilation.

Fan-blades, C C, are also fixed to the end-plate, B, nearest the commutator, at the back of which they maintain a current of air and prevent the accumulation there of dust or dirt. There are sixty bars in the commutator, each fitted with a lug, as shown, for connection with the armature conductor. The method of securing these bars is also clearly illustrated. Mica is employed not only for separating the bars from each other, but also for insulating them from the bush and cone ring by which they are secured. The bush, which is keyed on to the shaft, is of gun-metal, but in order to obtain a higher pressure the cone ring, R, and nut, N, are made of wrought-iron instead of gun-metal. The nut is caulked with copper to prevent oil creeping down the threads, and under each journal at T T, small tanks for waste oil are provided. The groove in which the collar of the brush rocking-bar turns is shown at H H This particular machine develops a maximum current of 120 amperes at 100 volts, the speed being only 250 revolutions per minute. It is compound-wound, the resistance of the armature being 0·1 ohm, of the series windings 0·017 ohm, and of the shunt-coil 30 ohms.

A type of machine, differing from those previously considered,

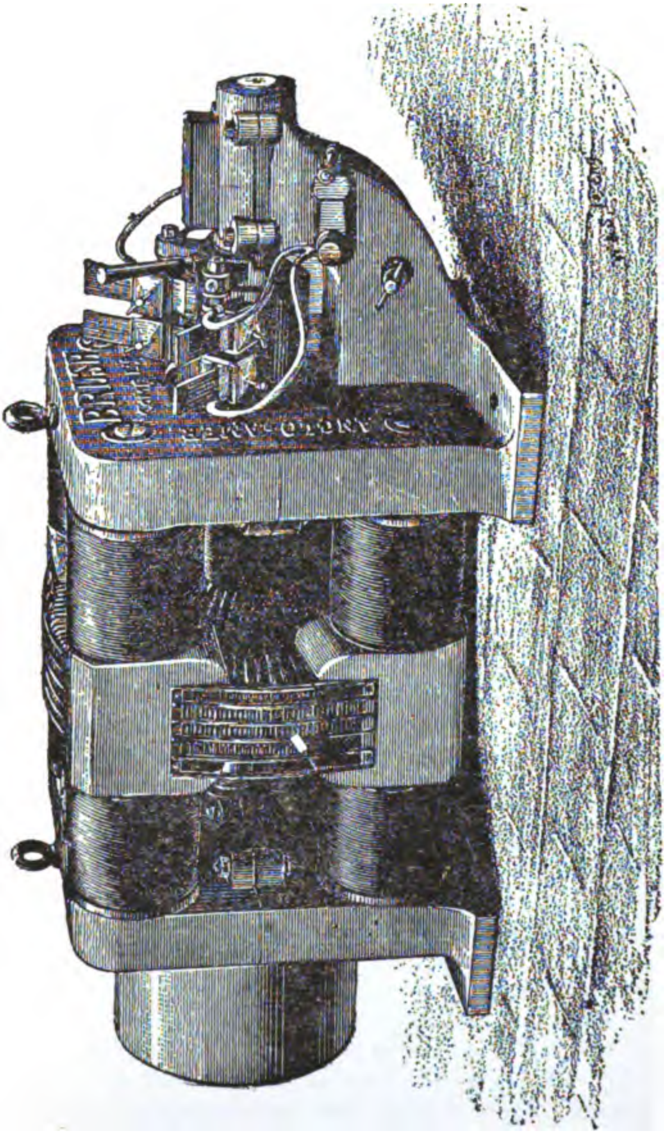


FIG. 196.

in regard both to the armature and the field, is illustrated in fig. 196. It is known as the 'Victoria' dynamo, and is a development by Mr. W. M. Mordey of a machine originally designed by Schuckert. In the earlier days of practical dynamo-building, engineers were much exercised by the comparatively large proportion of wire on ring armatures which cuts few or none of the lines of force, and which, therefore, is called idle wire. The Schuckert machine was designed to minimise this as much as possible, by flattening the armature ring, and extending the pole-pieces so as to make them embrace more of the wire on the flattened sides of the coils. The arrangement did not, however, altogether answer the anticipations, for by merely extending the pole-pieces, the density of the lines of force was diminished, and, with a magnet developing a certain strength of field, it matters little whether that field is spread out and the lines of force cut by a long piece of wire, or whether the field is more concentrated and only cut by a portion of the same wire.

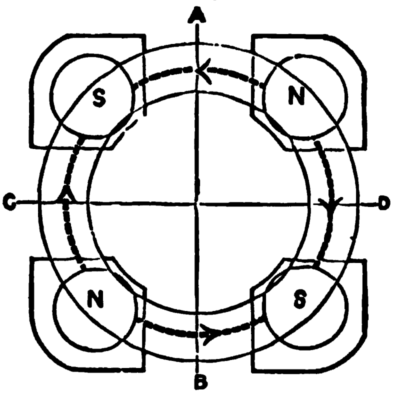
This form of armature, even when the best shape is given to the pole-pieces, is in reality slightly less efficient than either the ordinary ring or the drum form, but it is, nevertheless, a favourite, chiefly because it offers good facilities for ventilation, is very light in construction, and (owing to the sectional shape of the armature coils) there is but little tendency for the wires to fly out when driven at a high speed. Flat ring armatures are also usually set to rotate in a 'multiple field,' that is to say, the field is generated by four, six, or sometimes eight poles.

Fig. 196 illustrates a four-pole machine, four being the number most frequently employed. Each cast-iron pole-piece which partly embraces the armature has connected to it two cylindrical wrought-iron cores, the outer ends of these cores being bolted to the cast-iron standards forming the yokes.

The two coils on each pair of cores are so wound that their similar poles are adjacent to the cast-iron pole-piece between them, thus developing a strong field from the pole-piece. These pole-pieces are magnetised in this way alternately north and south, the arrangement of the entire field being that shown in fig. 197, where the direction of the lines of force through the armature core when it is at rest and the field undistorted, is shown by the arrow-heads. The lines of force enter at the outer circumference and also at both sides of the armature.

As the diameter of commutation is at right angles to the lines of force, and as in this multiple field there are two such diameters, A B and C D, two sets of brushes would appear to be necessary. This will be more apparent if we consider the inductive effects upon a single coil during a complete revolution. Supposing the coil to start from A, where its plane is at right angles to the lines of force, its upper portion will, in approaching the pole-piece, N, cut the lines of force from above, and in passing from N to D it will cut other lines, opposite in direction, from below, the result being that the induced current is in one direction only during the whole journey from A to D. Here the reversal takes place, for the coil, in approaching S, cuts these lines from above, and, passing S, cuts opposite lines from below, whence another continuous current is generated while the coil is travelling from D to B, where a second reversal takes place; and similarly with the other quadrants, the third reversal occurring at C, and the fourth at A. Or, viewing the matter from another standpoint, since the reversal of the current takes place at that moment when the maximum number of lines of force is projected through a coil, and as this maximum occurs at the point midway between each pair of pole-pieces (the field being still undistorted), it will be evident that the current must be reversed as the coil passes the points A, B, C, and D. Therefore, were the armature joined up in the ordinary way, one pair of brushes must be placed on the diameter A B and another on the diameter C D, to collect the current from all the coils.

FIG. 197.

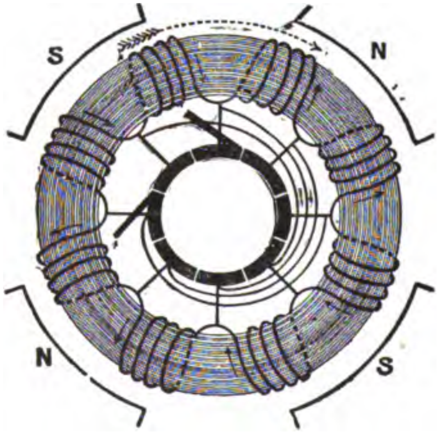


To avoid this inconvenient arrangement a simple modification is made in the winding. As every pair of diametrically opposite coils is at every stage undergoing precisely the same inductive effect as the pair of coils situated at right angles to it, it follows that every two such pairs of coils can be permanently joined together in parallel, for they are at every moment developing equal E.M.F.'s. By this device only two brushes are necessary, one being set 90° ahead of the other.

The method by which this 'cross-connecting' is effected in the Victoria machine practically consists in joining together the diametrically opposite commutator bars, as illustrated in fig. 198.

In this machine, as in every other, the reaction of the armature distorts the field and necessitates a forward lead being given to the brushes, which, however, are always separated by the same angle, viz. 90°. It must also be pointed out that there are always four paths open to the current through the armature, and that therefore the resistance from brush to brush is but one-sixteenth of what it would be were the whole of the coils joined in series. The low resistance thus obtained is an important feature in favour of multiple pole machines, for, in order to get with the ordinary ring or drum winding an equally low resistance, the conductor would have to be so massive that mechanical construction would be far less easy, and eddy currents would be generated in the conductor itself unless prevented by lamination.

FIG. 198.



In the case of a six-pole machine constructed on similar lines, either six brushes must be used, or, as is actually done, the commutator segments 120° apart, joined together in threes, two brushes being then employed with an angle of 60° between them.

In this class of machine, however, the adjacent pole-pieces, being of opposite polarity, must not approach each other too closely, otherwise an unduly large proportion of the lines of force will leak across the air-space instead of passing through the armature, and in any case the armature must be provided with sufficient iron to make the magnetic resistance low. Special care must also be taken with the lamination of the armature core. It will be remembered that the eddy currents induced in a rotating core, as in any other moving conductor, are at right angles to the lines of force of the field, and also to the direction in which the conductor is moving. In the case of the ordinary simple-field machine, the lamination of the armature presents little difficulty as the lines of force enter it from the outside circumference only. But the pole-piece *embraces* a flat-ring armature, and the lines of force enter at the sides as well as at the circumference, and it is therefore necessary to laminate the core in two directions, so as to avoid currents being induced either radially or in a direction parallel to the shaft.

For this reason an unusually large proportion of the space inside the coils of a flat ring armature is occupied by insulating material instead of iron.

Referring again to fig. 197, it will be seen that the direction of the lines of force through the armature is, as it rotates, frequently reversed, and that the number of reversals per revolution would be increased by increasing the number of poles. Such changes in magnetisation, if too rapid, would heat the core considerably, and impair the efficiency of the machine, and this is one reason why more than six poles are rarely employed.

Fig. 199 is a sectional side-elevation, showing the construction of the Victoria dynamo, fig. 200 being an end elevation, half in section, of the same machine.

The core is built up by winding iron tape, 0·012 in. thick and about half an inch wide (with thin paper insulation), round a stiff wrought-iron foundation ring, which is of the same width as the completed core, and is slotted on both edges at four equi-distant places. The four-armed gun-metal spider S (fig. 200) is made in two halves, held tightly together by hexagonal nuts screwing on to the shaft, to which also the hub is keyed. A bolt likewise passes through each of the arms, and when this divided spider is thus rigidly held in position, a little projection from the outer extremity

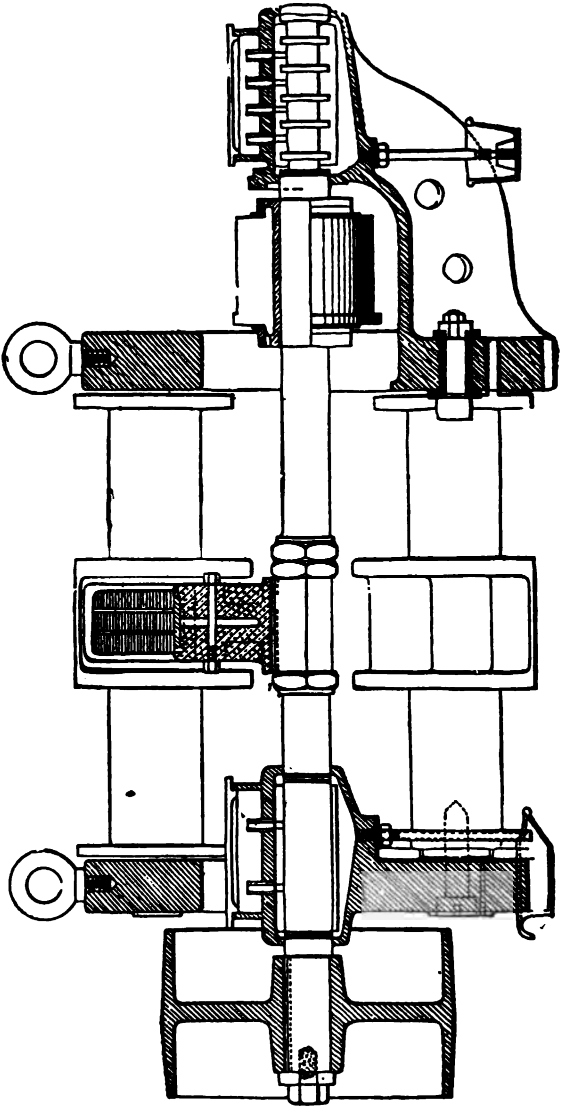
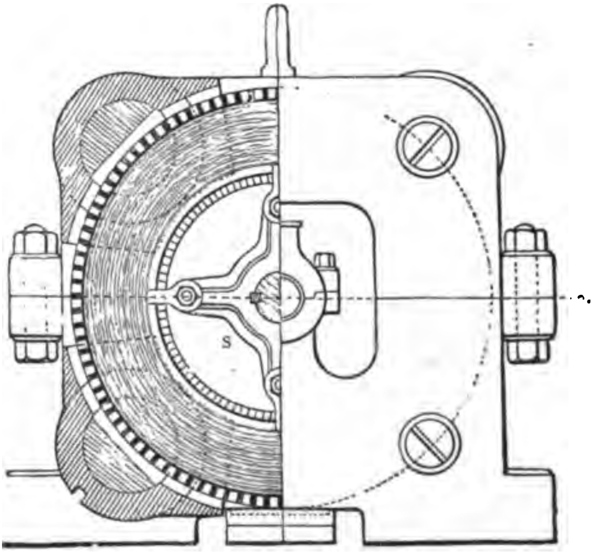


FIG. 199.

of each arm fits tightly into one slot of the wrought-iron foundation ring, and also extends a short distance into the core, a few of the inner layers being slotted for the purpose.

The section of the core is rectangular, and its radial depth is considerably less in proportion than that of the early flat ring armatures. Comparatively few of those lines of force which enter at the outer circumference penetrate through the whole depth of the core, and consequently the lamination near the foundation ring need not be carried to a very great extent to prevent the flow of currents in a direction parallel to the shaft. In some recent Victoria machines, the strips are, for this reason, narrower and more numerous towards the outer circumference than near the inside.

FIG. 200.



The armature conductor is rectangular in section, insulated with tape, and is wound in one continuous spiral round the core, the connections from the commutator bars being soldered on at the proper points on the inside of the ring.

The armatures of the smaller machines are, however, wound with ordinary circular wire, cotton-covered and well varnished.

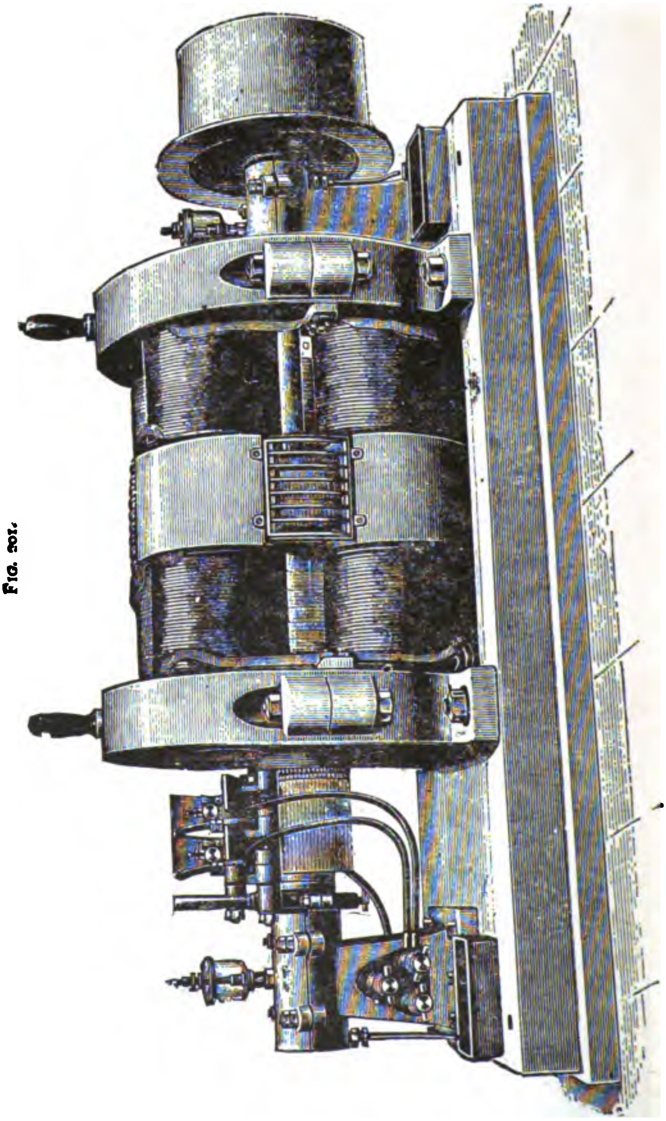


Fig. 201.

Each of the vertical standards forming the yokes is cast in two pieces, which are bolted together, so that the upper portion of each, with the two upper field-magnets, can be removed to afford access to the armature. This arrangement is shown in the figures, from which it will further be seen that the upper part of the bearings can also be detached, thus enabling the armature to be easily lifted out of its position when necessary for examination or repair.

As in all other machines, it is necessary for the space between the field-magnet and the armature to be as small as possible, and since the pole-pieces extend over the sides of the latter, it is clear that there must be no end play, or shifting of the shaft lengthways; this is effectually prevented by the long-grooved bearing shown to the right in fig. 199.

These machines are series, shunt, or compound-wound, as required. One built for the authors for educational purposes can, by means of a switch fixed on the top of the framework, be connected up for any one of these systems at pleasure.

The machine illustrated is intended to be driven at 1,000 revolutions per minute, and is then capable of developing 15,000 watts in the external circuit, at a terminal potential difference of 110 volts.

A multipolar flat ring machine is also manufactured by the Gülcher Company, and the latest type of this, known as the 'Battersea' dynamo (fig. 201), is worthy of special notice. As has been remarked, such machines, while slightly less efficient than other forms, present in some respects fewer difficulties in construction, and the Battersea dynamo is, from a mechanical point of view, as well as electrically, an exceptionally good specimen of its class.

Fig. 202 gives a longitudinal section through a machine of recent construction, a side elevation being shown in fig. 203. It is a four-pole machine, having an output of 12,000 watts.

The foundation of the armature core is the rim of a strong gun-metal wheel, which has four radial arms. The hub of the wheel bears on one side against a collar on the steel shaft, as shown to the right in fig. 202; it is held tightly in position on the other side by a steel nut which screws on to the shaft. The core itself consists of soft iron wire rectangular in cross-section, and insulated with cotton. It is wound round the foundation-ring under high tension, the core thus built up being very strong and rigid.

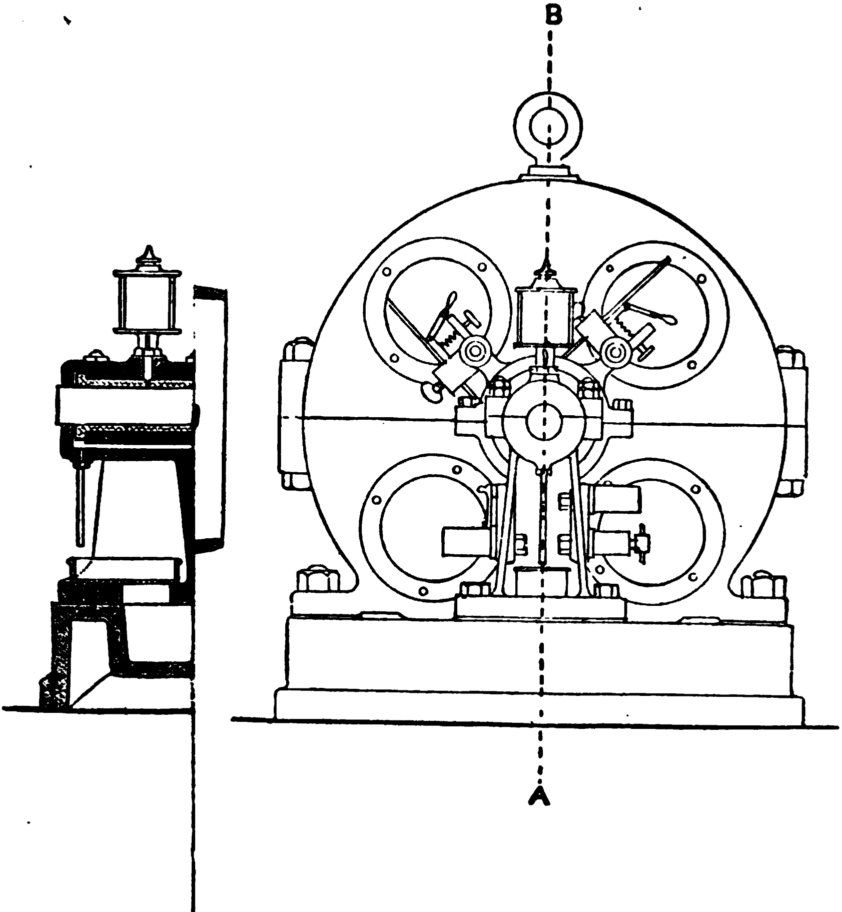
We have referred to the necessity for lamination in two directions; and the smallness of the wire, and the efficiency of its insulation practically eliminate eddy currents, while the thinness of the insulation and the tightness of the winding reduce the waste of space to the lowest possible limit.

The armature conductor, which is a copper strip, is wound over this core (embracing also the rim of the supporting wheel) in a single layer · the strip is rectangular in section, its dimensions being calculated so as to just occupy the allotted space round the circumference, and thus the distance between the pole-faces and the core is made a minimum. By the device of cross-connecting, the current is collected from a single pair of brushes, placed 90° apart. The method of connecting diametrically opposite pairs of coils in parallel is unique. On the shaft between the armature and commutator is fixed a wooden sleeve, over which a number of flat copper rings are slipped. These rings are carefully insulated, and each has two lugs projecting at opposite extremities of a diameter; a radial saw cut is made in each lug, just large enough for a copper conductor strip to be pressed in and soldered. The rings are so arranged that their lugs form a spiral round the shaft, and those connecting strips which lead from diametrically opposite coils of the armature to the commutator, are soldered to the lugs of the same ring. In this way diametrically opposite bars of the commutator are joined together: one such connection is shown at the ring nearest the commutator in fig. 202.

The circular cast-iron end frames forming the yokes to the field-magnets are in two halves bolted together, the lower half being also bolted to the bed plate, as shown in the illustrations. These yoke-pieces are very massive, and, as the surfaces of contact between them and the wrought-iron cores are large and close-fitting, the magnetic resistance is low, and a large proportion of the lines of force are led into the armature.

The whole armature conductor offers but little resistance, and as, by the cross-connecting, this is reduced to one-sixteenth of the resistance which would be offered were all the coils joined in

FIG. 203. *To face page 374.*



series, but little power is absorbed in the armature. and the machine is self-regulating through a considerable range

The commutator consists of eighty copper bars. with mica insulation, fixed, as shown in the drawing, by a gun-metal nut and washer, over a gun-metal sleeve.

In smaller machines, circular copper wire, instead of rectangular strip, is employed for the conductor, and the magnetic resistance of the core is even further reduced by covering the iron wire with silk instead of cotton, the former occupying much less space than the latter.

In concluding this chapter, we may with advantage pass a few further remarks concerning the losses which reduce the efficiency of a dynamo. Omitting the power absorbed in overcoming the conductor resistance, which can easily be calculated, the losses may be classified under three general heads: (*a*) Mechanical friction; (*b*) Eddies in conductor; (*c*) Losses in armature core. The friction occurs principally at the bearings—for the commutator brushes should exert only just sufficient pressure to insure reliable contact—and the loss due to this cause increases regularly with the speed at which the machine is driven. When the conductor is massive, as in the case of a bar armature, the eddy currents in it may be sufficiently important to absorb a considerable amount of power, and, as we have seen, such conductors are frequently laminated, or sometimes braided wire is employed, to prevent the circulation of the currents. Lamination of the iron core, if properly performed, also reduces to a minimum the eddies in the iron; but there is another source of loss which arises when lines of force passing through iron are rapidly reversed or altered in direction, due to a phenomenon known as hysteresis. This loss appears to be the result of a kind of internal friction between the molecules of the iron, when they change their position, as we believe they do, under the influence of the magnetising force. At any rate, it is not possible to project lines of force through iron, or alter their position, without a small amount of work being performed independently of that resulting in eddies.

With one particular specimen of iron, through which the magnetic induction was 18,000, Dr. Hopkinson estimated that 13,000 ergs were expended in twice completely reversing the magnetism, apart from the energy reappearing as eddies. But as any mechanical or other cause which sets the particles of the iron vibrating reduces the energy lost by hysteresis, such calculations are not directly applicable to the case of the iron employed in a dynamo machine.

It is a most important matter to separate, if possible, these sources of loss in any dynamo, in order to ascertain what parts of the machine, if any, need altering in design. This separation has very recently been effected practically by Mr. W. M. Mordey, who plotted his results in the curves shown in fig. 204. The machine experimented with was a direct-current Victoria dynamo, with an output of 18,000 watts, the speed being varied up to 1,200 revolutions per minute. The armature core consisted of iron strip, 0·012 inch thick, with thin paper insulation, the cross-section of the iron in the core being 12 square inches, and the magnetic induction through it 12,300 C.G.S. lines.

The dynamo had four poles, and, therefore, the lines of force through the core were reversed twice in every revolution.

The machine was driven with the field-magnets disconnected, the iron having been deprived of its magnetism by a rapidly alternating current; and the power then absorbed, measured by a transmission dynamometer, gave, at various speeds, the value of the power spent in overcoming the mechanical friction. Since the iron in the magnet cores always retains some magnetism, a small amount of power would be absorbed in the production of weak eddy currents, were this residual magnetism not carefully eliminated.

In fig. 204, O M, representing the friction loss, is plotted below the base line, so that the relation between the other curves can be more clearly seen.

In order to obtain the total losses in the iron core, the field was separately excited to its normal strength by means of secondary batteries, and the armature core, without the copper conductor, driven at various speeds, the power absorbed in driving being measured as before.

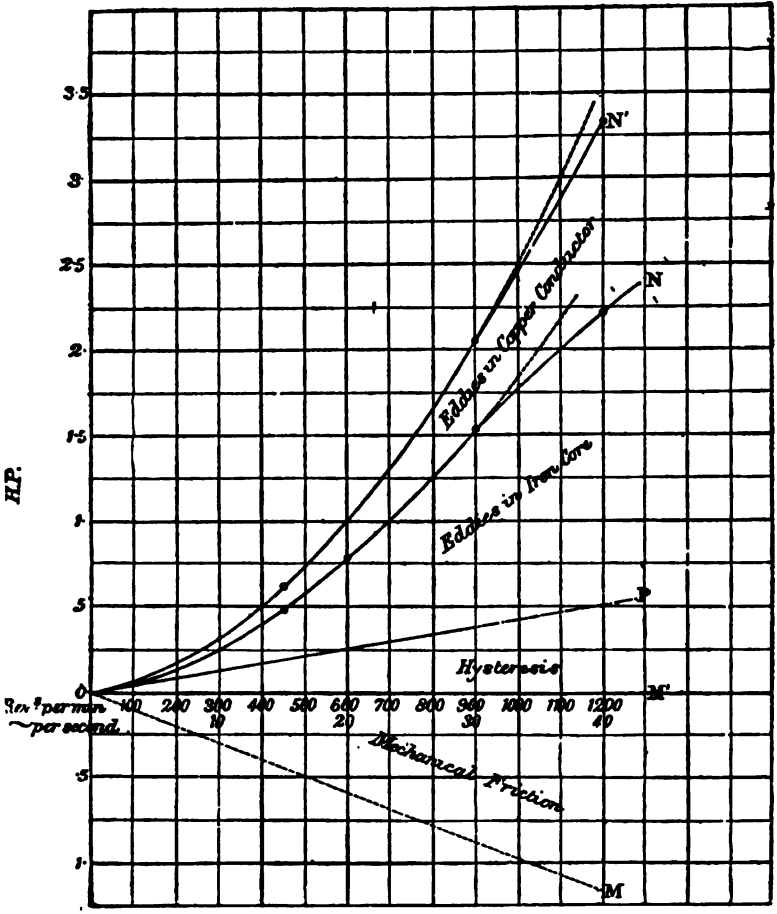
This power is the sum of that absorbed by friction, eddies in the core, and hysteresis; and by subtracting the friction the two latter quantities remain, and are plotted at O N in the figure.

On winding the armature and repeating the experiments, the curve O N′ is obtained, and the difference between the ordinates

FIG. 204.

Determination of Losses in Dynamo Armature

MORDEY.



O N′ and O N represents the loss due to eddies in the copper conductor.

But the important problem is to find a means of separating the hysteresis and eddy current losses in the core; this was accomplished, and the line O P represents the loss due to the former.

The method of separation is simple, and depends on the fact that while the loss due to the eddies varies, with a given number of lines of force, as the square of the speed, the loss from hysteresis is proportional to the speed simply.

Therefore, if two speeds are taken, such that one is double the other for instance, 450 and 900 (see the figure)—the height of the hysteresis ordinate, from O M′ to O P, at the higher speed, will be twice the height of the ordinate at the lower speed; while the height of the eddy-current ordinate from O P to O N will be four times as great at the higher as at the lower speed.

After a few trials, the two points between O M and O N which satisfy these conditions can be found; and the line O P, drawn through these points, separates the loss caused by hysteresis from that due to eddy currents.

The curves O N, O N, show the actual loss experimentally observed, but a dotted branch line is added to each, which indicates the curve which would be obtained if the rate of loss of power had been maintained with the increase of speed up to 1,200 revolutions. It will be observed that the actual loss agrees with the calculated loss until a speed of 900 is reached. from which point it falls below the calculated value. The reason for this is not altogether explainable at present, but, on account of its importance, efforts will doubtless be made to determine the relative magnitudes of the various reactions which take place.

The vertical sides of the squares represent 0·25 of a horsepower, while the horizontal sides represent 100 revolutions per minute, or 3·3 complete magnetic reversals[1] per second; and it will be observed that although the lamination of the core has been carried to a high degree, yet the loss due to eddies is considerable, and cannot by any means be ignored. One object of these experiments was to demonstrate that, however well laminated, the iron cores in the armature of an alternating-current dynamo are the seat of a considerable amount of loss, and this has un doubtedly been proved to be the case. The departure from the calculated rate of loss at the higher speeds, as evidenced by the bending down of the curves, prevents, however, the method being directly applied to alternating machines, where the reversals are considerably more rapid than when the disturbing causes begin to manifest themselves. But the experimenter is to be congratulated upon having produced a method which is practical, and apparently reliable in the case of direct-current machines running at a fair speed, and which, at any rate, forcibly draws attention to causes of loss which, it is often assumed, are so unimportant that they can be ignored.

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[1] The symbol ~ is used to denote a complete alternation of the current. It is, in fact, the sine curve (fig. 120) in miniature.

CHAPTER XI.

DIRECT CURRENT DYNAMOS (OPEN COIL).

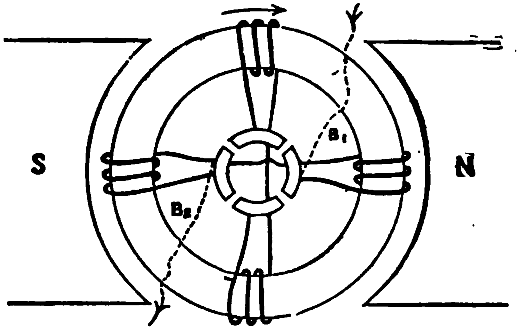
In the armatures of the direct-current machines hitherto described, all the coils are connected together, and the junction of each adjacent pair is joined to a bar of the commutator. But there is another method of constructing an armature, in which the coils are kept quite separate, each having in the simplest form a separate two-part commutator. The former are known as 'closed-coil,' and the latter as 'open-coil' armatures. Machines for developing very high electro-motive force are usually built with open-coil armatures, an E.M.F. of 2,000 volts being not uncommon; hence such machines are used for electric lighting in cases where the type of the lamps and their disposition are such as to require the transmission of the current through a high resistance. In a closed-coil armature the E.M.F. generated by every coil in any and every position, excepting at the moment when it is short-circuited by the brush, forms a part of the total E.M.F. of the machine. On the contrary, in an open-coil armature the current is collected from a coil while it is in the position of greatest activity only, or while the E.M.F. induced in it is at its maximum, the coil being thrown out of circuit during the time that it passes through the period of least activity. At the beginning of this latter period another coil enters the best position, and commences to feed the circuit. The coils may be wound either on the ring or drum principle, but in the former case the two coils at opposite extremities of a diameter are joined together in series and may be treated as one coil.

Many of the elementary principles examined in connection with the machines already described, hold equally well for those with open-coil armatures, and while it is unnecessary to again enter into a lengthy discussion of these matters, we may say, briefly, that the field will be distorted in the same manner, and that the position of maximum activity for any coil will be that in which its plane is parallel to the lines of force of this resultant field. To minimise the distortion and to obtain a high E.M.F. for a given speed of rotation, the field-magnets must also develop as strong a field as possible.

The high E.M.F. developed requires, however, greater precautions as regards insulation than are taken with ordinary closed-coil machines, and this point must be carefully kept in view in designing and selecting the materials for the insulation both of the armature and of the field-magnet coils. In closed-coil machines the potential difference between adjacent coils and commutator bars being only a fraction of the total potential difference at the brushes, the difficulties in the way of efficient insulation for high E.M.F.'s are not so great as might appear at first sight. But while in a closed-coil machine the number of active conductors joined in series is never more than half the total, in an open-coil machine the proportion is not only greater, being usually about two-thirds, but consists of those in the most active positions, so that the latter class are more suited to the development of high E.M.F. It is evident, however, that if the coils are cut out of circuit while they are fairly 'active,' there must be some means of dealing with the inevitable sparking; it must either be minimised by some arrangement of the commutator, or its destructive action prevented.

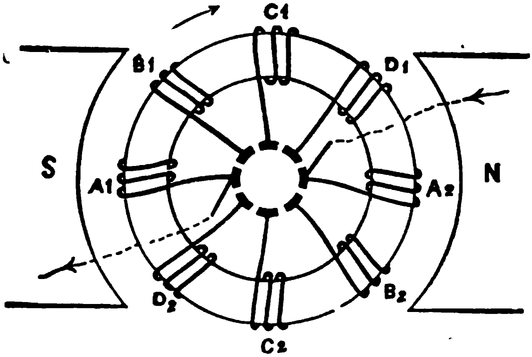
The fundamental principle of all open-coil dynamos is illustrated in fig. 205. Two pairs of coils are shown, wound round an iron ring, at right angles to each other. The commutator has four parts, or, strictly speaking, there are two two-part commutators, each part forming a fourth of a circle; and each of these two-part commutators is connected to the ends of its particular pair of coils. Two flat springs, B_1 and B_2, act the part of brushes, and to simplify matters we will assume that the field is undistorted. Since we desire to take the current from the coils while they are at their maximum activity, the brushes must be placed parallel to the lines of force, a position exactly opposite to that of the brushes on a closed-coil machine. The two horizontal coils by this arrangement deliver their current to the external circuit, while the vertical ones, being comparatively idle, are entirely disconnected. The activity of the horizontal pair decreases from this point, and when the armature has revolved through another

Fig. 205.



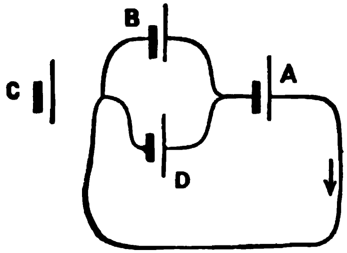
45° they are thrown out and the other coils begin to feed the circuit. Each pair is thus joined up and disconnected alternately for a period equal to a quarter of a revolution, and an ammeter placed in the external circuit would indicate a current, continuous

Fig. 206.



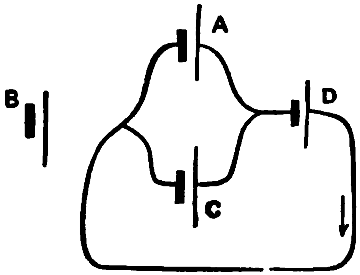
in direction, but fluctuating considerably in strength. Greater steadiness, that is to say, a nearer approach to constancy, can be obtained by increasing the number of coils, although it is not possible to get a current so nearly constant as that which a good closed-coil dynamo can generate. In fig. 206 the number of coils is increased to eight, that is, four pairs. The two coils at opposite extremities of a diameter, A_1 A_2, for instance, are joined together to form a pair as before, but to avoid a complicated diagram this connection is not shown and the distortion of the field is again ignored. Each pair has its commutator, the segments of which are (including the insulating space between the adjacent segments) one-eighth of a circle, or 45° in length, and therefore each pair of coils is connected to the brushes for one-eighth of a revolution only. The maximum E.M.F. is the same as in the last case, and as the minimum does not fall so low, the resulting current is more nearly uniform. It will probably occur to the student that the coils D_1 D_2 and B_1 B_2, although far less active than A_1 A_2, are yet in a position where they can generate a considerable E.M.F. and that they might with advantage be allowed to assist. But they must not be joined up in *parallel* with A_1 A_2, since their E.M.F. is so much less. Otherwise we should get a result similar to that obtained when a Grove cell and a Daniell cell are joined up in parallel, that is, the Grove cell urges a backward current through the Daniell because it has a higher E.M.F.; and the external circuit gets actually less current than if the latter cell were removed altogether. But if the two are joined up in *series* then the external circuit gets the whole current resulting from the sum of their two E.M.F.'s. In the same way, if the effect of the coils in positions of less activity is to be utilised, they must be joined up in series and not in parallel with those developing the higher E.M.F. We will explain how this matter is arranged in what is perhaps the best open-coil machine, viz. the 'Brush' dynamo. Now in the case of a set of four pairs of coils rotating in a uniform field, as in fig. 206, it is clear that at one time, only one pair of coils can be in the best, and only one pair in the worst, position for generating a current. On the other hand, it is possible for two pairs to be equally active in an intermediate position, and this will happen when they make an angle of 45° with the lines of force, that is, in the position occupied by B_1 B_2, and D_1 D_2. In the Brush dynamo, when the armature consists of eight coils, two pairs of brushes are employed, one collecting the current from the coils in the best position only, A_1 A_2, while the other joins up the two pairs of coils in the intermediate position, B_1 B_2, D_1 D_2, in *parallel*, and collects the current from them. The two pairs of brushes are joined in series, and thus the E.M.F. of the intermediate coils is *added* to that of the coils in the best position, only one pair, as C_1 C_2, being thrown idle at a time. As the intermediate coils are placed in parallel their E.M.F. is the same as that of one of them, the resistance being, however, halved. In order to make this quite clear we may represent a pair of coils as we do a primary cell, and then show the arrangement, as in fig. 207, where A represents the most active, and C the least active pair of coils, B and D being those in the intermediate stage. When the armature has turned through another 45°, the B coils are idle, the D are at the maximum, and the A and C in parallel, as shown in fig. 208.

FIG. 207



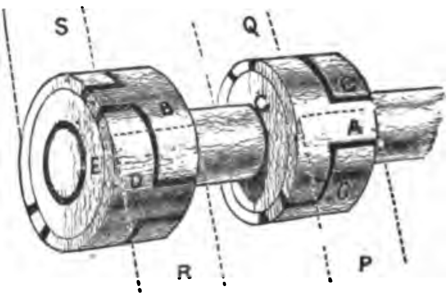
The commutator, by means of which these changes are effected, is illustrated in fig. 209. It is divided into two portions, each complete in itself, and consisting of four thick T-shaped pieces of brass separated from the shaft by rings of insulating material, E G: the T-shaped sections being insulated from each other by air-spaces. The brushes, P Q R S, are formed of flat copper strips, and, as shown by the dotted lines, are sufficiently wide to cover the whole width of the commutator rings. The ends of a pair of coils are joined to diametrically opposite segments or sections as indicated in the figure, the lettering in this illustration corresponding to that in fig. 206. One of the commutator rings is fixed on the shaft 45° in advance of the other, the consequence of which is

FIG. 208.



that when, on one ring, each of the brushes is resting on one section only, as at A, then each brush on the other ring is in contact with two sections, as at B, D. The student will perceive that in the case illustrated the sections of the left-hand commutator ring have joined to them the two pairs of coils which are in the intermediate position, and therefore require to be placed in parallel, while the right-hand ring has joined to it the pair (A) which is in the best position and also the pair which, being inactive, is disconnected.

FIG. 209.

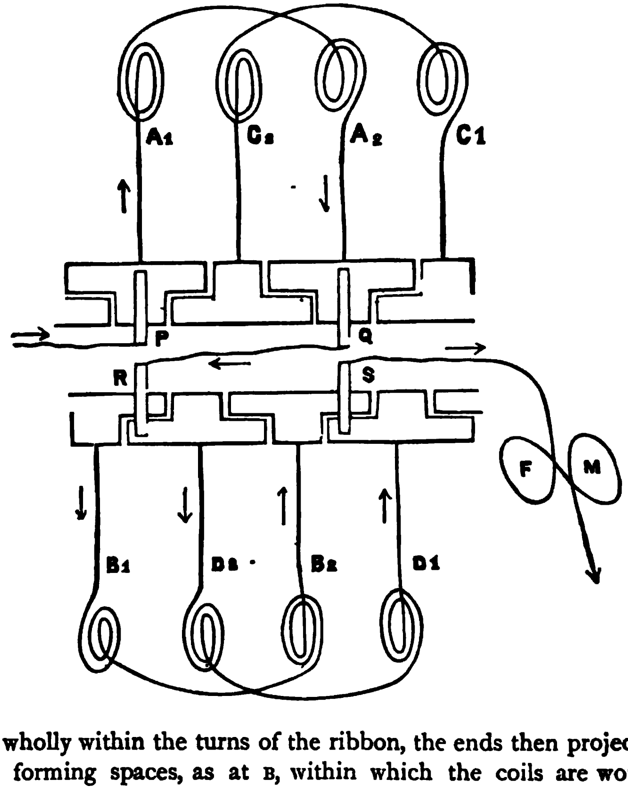


In fig. 210 the two double commutators are developed or spread out, side by side, to make the matter clearer, the lettering of the coils being the same as in fig. 206. The path of the current is easily traced. It passes round the pair of coils, A_1 A_2, the brushes P and Q (by which it enters and leaves), each resting on one section only, because those coils are in the best position. The current then passes direct to the brush R (on the left-hand part of the commutator), which, resting on two sections, affords a path through B_1 B_2 and D_2 D_1, in parallel. The brush S, by which it finally leaves, is connected to one end of the field-magnet coils, F M; the coils C_1 C_2 are disconnected. Such is the action which takes place in a Brush dynamo having four pairs of coils in its armature

The actual machine is depicted in figs. 211 and 212, the latter of which is an elevation from the commutator end. The cores of the field-magnets are almost oblong in section, and are securely bolted to cast-iron uprights which form the yokes. These two horizontal horse-shoe field-magnets are placed with their similar poles opposite each other, and project a powerful field round the armature. There is an unusually large quantity of iron in the armature core, and careful lamination is needed to reduce the loss of energy due to eddy currents.

The method of building up this core is illustrated in fig. 213. A thin soft iron ribbon is wound in a continuous spiral round an iron foundation ring A^1 Between the successive convolutions of the ribbon, and held by them as the process of construction is carried out, are placed H-shaped iron stampings, S, of the same thickness as the ribbon. The connecting portion of these stampings lies wholly within the turns of the ribbon, the ends then projecting and forming spaces, as at B, within which the coils are wound. The stampings are all of one size, so that adjacent sets in the inner portion of the ring are nearer to each other than in the outer portion, while the sides of the channels in which the wire is wound are parallel. The whole is rigidly fixed together by means of

FIG. 210.



insulated bolts, *b*, passed radially through the H-pieces, the spiral ribbon and the foundation ring, A′, as shown in the sectional view. The stampings and ribbon are, however, proportionally much thinner, and the number of turns is much more numerous than shown in the figure. The loss occasioned by eddy currents is thus reduced to a minimum.

The armature coils are insulated from the core by sheets of canvas and paper, treated freely with shellac varnish, the layers of wire being insulated by cotton-cloth. The ends of each pair of coils are carried along the shaft to their proper sections of the commutator.

The field-magnet coils are also carefully insulated from their cores by vulcanised fibre and varnished paper, the

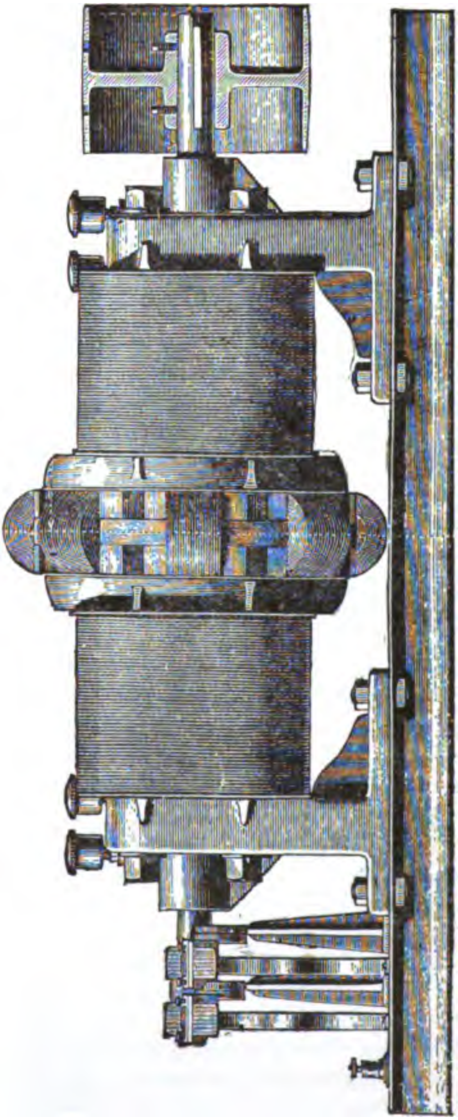
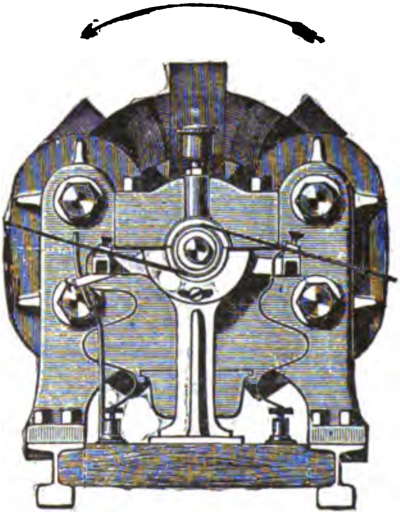


FIG. 211.

different layers being separated as in the case of the armature by cotton-cloth. These coils are joined up in series, and as the current generated by the machine fluctuates more or less, there is a tendency for eddy currents to be induced in their unlaminated cores. This is overcome by the simple device of interposing between the coils and the iron a thin tube of copper, in which the currents are induced instead of in the iron. These induced currents tend to reduce the fluctuations of the primary current.

FIG. 212.



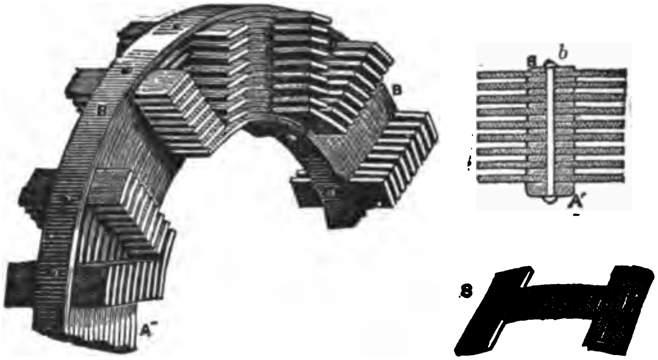
The pole-pieces are extended so as to embrace an unusually large portion of the armature, and the opposite pole-pieces being similarly magnetised, the lines of force are not projected axially through the armature; but entering the core on both sides, by the projections formed by the H-pieces, tend to pass circumferentially round a portion of the core and leave it at another set of H-pieces, near the other poles, the lines of force being in this way urged through and cut by the coils as they rotate.

The diameter of greatest activity is approximately in a line with the upper horn of the right-hand pole-piece, and the lower horn of the left-hand pole-piece (fig. 212), as will be gathered from the position of the brushes, the direction of rotation being left-handed as viewed from the commutator end. As the machine is regulated to give a nearly constant current, the reaction of the armature on the field, and therefore also the lead of the brushes, varies only very slightly under ordinary changes in the load.

The machine illustrated is designed to supply 55 arc-lamps in series, with a current of 10 amperes. The figures are both drawn to scale, the principal dimensions being: length of bed-plate 7 ft. 10 in., width 2 ft. 5 in., height of highest point 3 ft. 1½ in., outside diameter of armature 2 ft. 9 in. The diameter of the shaft is 2¾ in., its centre being 1 ft. 9¼ in. above the ground line. The pulley measures 18 in. by 12½ in.

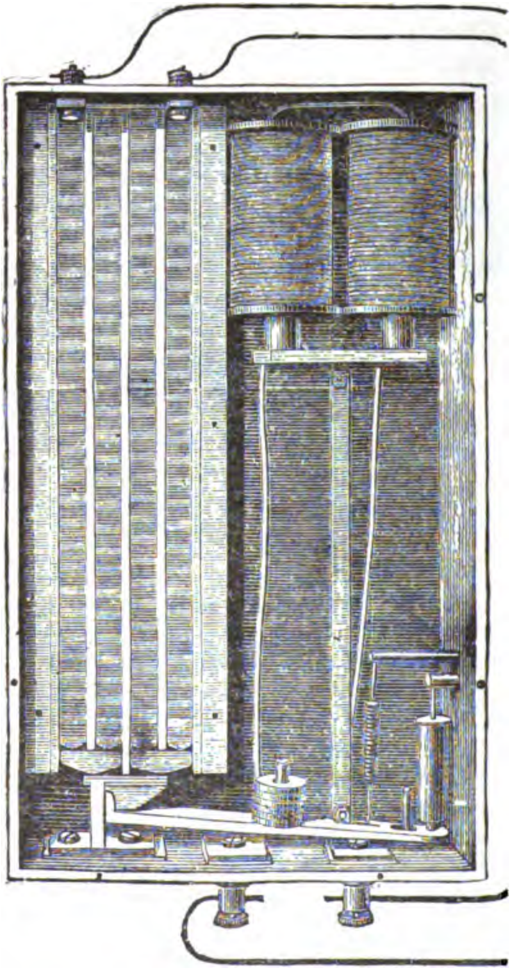
The brush-holders are connected to terminals on the bed-plate by means of flexible copper strips, the method for adjusting the brushes being shown in fig. 212. Each pair is carried by a lever, which can be turned round the shaft, its range being, however, limited by the length of the slot in the semicircular collar directly under the shaft. One end of the lever is furnished with a small projection riding over a curved guiding-fork, the position on the fork being fixed by means of a set screw.

FIG. 213.



Although this machine is capable of driving as many as 55 arc-lamps joined in series as its maximum load, the number of lamps actually switched in circuit varies considerably from time to time; but the act of switching out a lamp reduces the external resistance, and the machine being series wound, the current strength is proportionally increased. It is nevertheless essential that under all conditions the same current strength—viz. 10 amperes—should be maintained: hence some regulating device becomes necessary. The regulator devised for this purpose by Mr. Brush is ingenious, and is illustrated in fig. 214. It consists of four vertical columns of thin retort-carbon plates separated by vertical slate partitions. These columns are joined in series between the two terminal screws at the top, connection being made between the two inner columns at the top, and between the outer pairs of columns at the bottom, by means of carbon slabs. Wires are led from the two top terminals to the ends of the field-magnet coils, across which these carbon columns form a shunt, whose resistance can be varied by altering the pressure upon the plates. This pressure is automatically increased when the current rises above its normal value, and the resistance of the shunt being thus reduced, a larger proportion of the current is abstracted from the field-magnets, and the strength of the field and current kept at their proper value. The method of accomplishing this is illustrated in the figure.

FIG. 214.

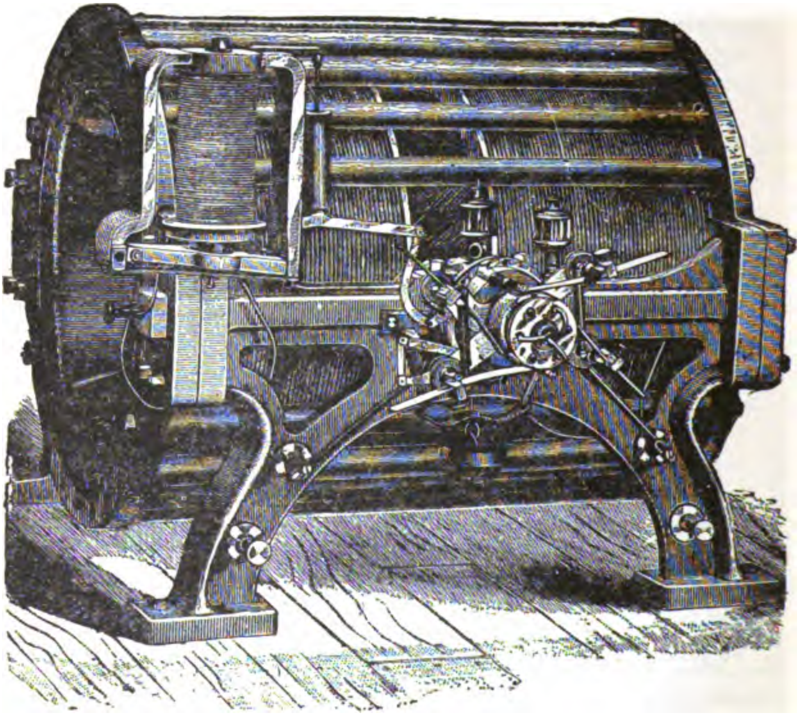


The two solenoids are joined up in the main circuit by way of the terminals shown at the bottom. Projecting partly into the coils, are two soft iron cores, permanently fixed to a common yoke-piece, the centre of which carries a brass rod attached at its lower extremity to one end of a lever, whose fulcrum is a knife-edge at its extreme left end. When by the switching out of lamps, or from any other cause, the main current passing through the solenoids increases, the cores are sucked upwards with greater force, and the block on which the four columns rest is raised through a short distance by the lever, thus compressing the carbon plates and reducing the shunt resistance, with the result that the current in the field-magnets is proportionally reduced. A dash-pot is attached to the free end of the lever to prevent sudden or jerky movements, the normal adjustment being obtained by means of a spiral spring and a few small weights slipped over a vertical pin.

Brush dynamos are made in a great variety of sizes and forms, to fit them for various classes of work, the armature being sometimes wound with twelve coils, in which three sets of commutators and brushes are required. A very remarkable machine is one constructed for the purpose of smelting aluminium, the current required being 3,200 amperes with an electro-motive force of 80 volts. Its actual speed when developing its maximum power is a little over 400 revolutions per minute. The cores of the field-magnets are of cast-iron and cylindrical in shape, with a diameter of 11 inches and a length of 16 inches, the total weight of the copper with which they are wound amounting to 542 lbs. The armature contains 825 lbs. of copper wire, and has an iron core weighing 1,600 lbs. The machine measures about 15 feet long and 4 feet wide, and stands 5 feet high.

The only other form of open-coil dynamo in general use is the Thomson-Houston, of which a general view is shown in fig. 215. It is a machine by itself, having many peculiar features, altogether different from those of any other with which we have dealt. There are two field-magnets placed horizontally, with their opposite poles facing each other. There is comparatively little iron in the cores, each of which consists of a cast-iron tube flanged at both ends, and provided at the armature end with a spherical cavity to form the pole-piece. The shape of the armature itself is that of a slightly flattened sphere, somewhat like an orange, and it revolves between and partly within the cup-shaped pole-pieces The wire on each field-magnet core is wound in the space between the flanges, the outer flanges of the two cores being wider than the inner ones, and affording thereby, means for a number of wrought-iron bars to be bolted through them. These bolts add materially to the mechanical strength of the machine, protect the coils from injury, and form the yoke of the field-magnets. The machine, which, on account of the small quantity of iron employed in its construction, has but little weight, is supported by comparatively light but strong standards, which are bolted to lateral projections from the flanges of the field-magnet cores. These standards also carry the armature bearings.

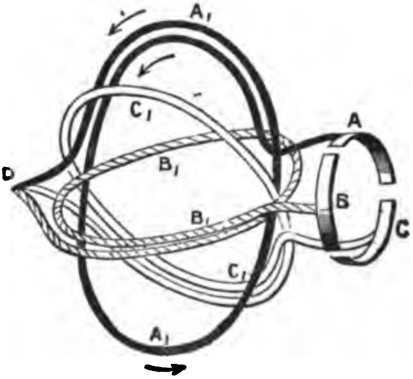
FIG. 215.



The manner in which the armature core is built up is also interesting. Upon the shaft are keyed two stout cast-iron discs, each provided on its inner face and near its periphery with an annular groove. About a dozen wrought-iron ribs are sprung into the pair of grooves, so as to bridge the space between the discs, and form a circular framework, round which a number of layers of varnished soft iron wire is wound. This forms the complete core, into which, however, a number of wooden pegs are fixed, to guide the winding of the coils and to hold the wire in position. Before the coils are wound on, the core is insulated by layers of paper fastened by means of gum-lac.

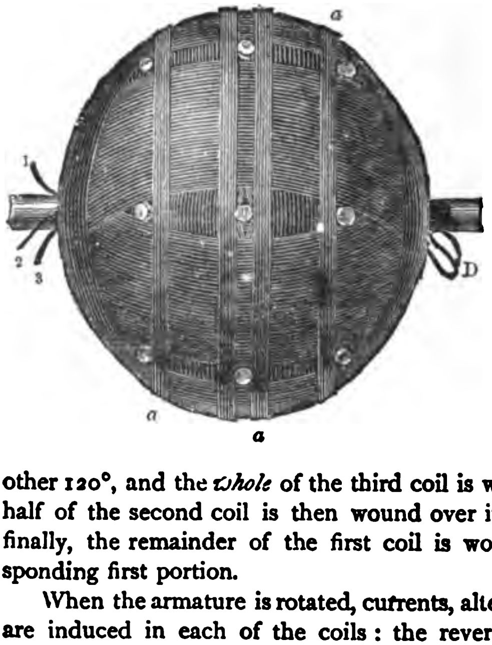
The armature consists of only three coils, and fig. 216 illustrates, in the simplest manner, the way in which they are wound. The inner ends of the three coils are soldered together, as at D, and the junction carefully insulated. Starting from this junction, each coil is wound over the core, with an angle of 120° between the middle portions of the coils, the three free ends being joined, one to each segment, A, B, or C, of the three-part commutator. A view of the completed armature is shown in fig. 217, and it will be observed that the overlapping of the coils near the shaft causes the form to become almost spherical. The junction of the three coil-wires is shown at D, the free ends, 1, 2, 3, being brought out on the other side of the armature. The coils, when finished, are bound round with four binding wires, *a a*, passing several times round the armature to prevent the coils 'flying.'

FIG. 216.



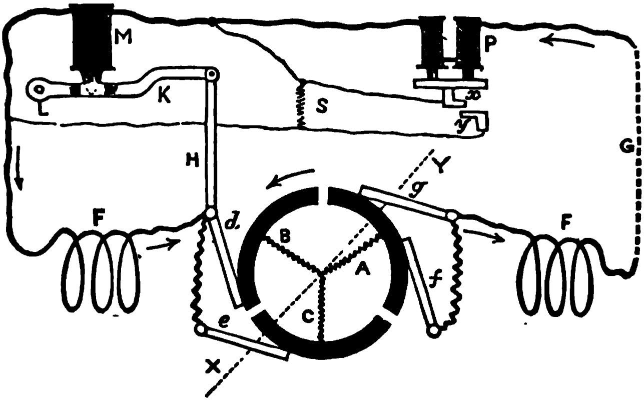
It is essential that every armature should be truly balanced, not only mechanically, but also electrically—that is to say, all the coils should be of the same area, and equidistant from the core and pole-pieces, so that the inductive effect on each is precisely the same, and they should be all of the same length and of the same resistance. It is evident, therefore, that it would be inexpedient to wind the three coils in this spherical armature completely one over the other. But the length and the average distance from the core of all the coils is made equal by a very simple method of winding. Starting at the junction D, half of one coil is wound; then, 120° further round the core, half of the second coil is wound; yet another 120°, and the *whole* of the third coil is wound. The second half of the second coil is then wound over its first portion, and, finally, the remainder of the first coil is wound over the corresponding first portion.

FIG. 217.



When the armature is rotated, currents, alternating in direction, are induced in each of the coils: the reversal, as usual, taking place in each case when the plane of the coil is at right angles to the lines in the resultant field. The reaction of the armature, of course, distorts the field somewhat, and shifts it round through a certain angle in the direction of rotation, as shown by the dotted line X Y in the lower part of fig. 218. In this figure, each radial line, A, B, C, represents one of the armature coils, united in the centre and joined to its respective commutator segment. The current is collected along the diameter of maximum activity, X Y, by two pairs of brushes, *d*, *e*, and *f*, *g*, each pair being electrically connected. The two brushes forming a pair are so placed that one presses on the commutator at a distance equal to 60° in front of the other. The consequence of this arrangement is that the most active coil is joined up in series with the remaining two less active coils, which are joined together in parallel. In the case shown in fig. 218, the coil A is approaching the best position; while B and C are in the intermediate stage, and are therefore joined up in parallel. The resulting E.M.F. is, consequently, that due to the mean E.M.F. of B and C, added to the separate E.M.F. of A. As the armature rotates, B approaches the best position, and its commutator segment alone is then in contact with the brushes *d*, *e*, while C and A, which are brought to the intermediate positions, are joined in parallel. These changes are continually repeated as the coils pass through the different portions of the field.

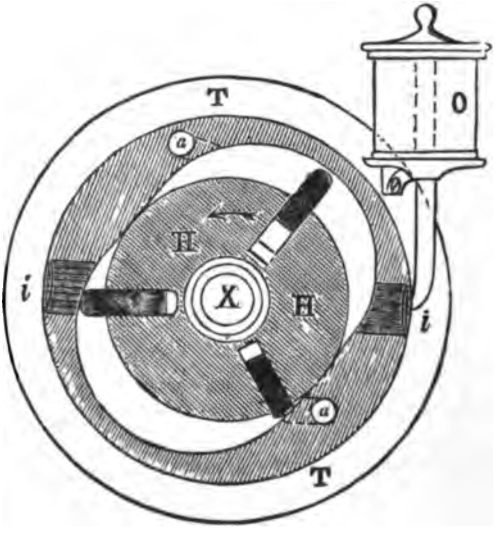
FIG. 218.



As in the case of the Brush dynamo, this machine being series wound and used on a circuit of high resistance for driving a large number of arc-lamps joined in series, the switching out of any of the lamps tends to cause an increase in the current strength, while, conversely, the switching in of lamps causes a diminution. Hence, in order to keep the current at a nearly constant strength, some regulating device is necessary. The method adopted consists in simply altering the position on the commutator of the two brushes forming each pair. It will be observed, from the commutator in fig. 218, that, the brushes being 60° apart, no coil is thrown out of circuit at any part of the revolution, and this is what we may call the normal state of affairs. When, however, the current falls in strength, each pair of brushes is closed up automatically, so that all the coils are, in turn, disconnected for a moment when they are passing the neutral position, and are therefore nearly idle. The E.M.F. of the two coils in parallel is the mean of their individual E.M.F.'s, and is, obviously, lowered by a comparatively idle coil, so that, at the moment when the idle coil is thrown out, the E.M.F. resulting from the other of the two coils in question is greater than it would be were they both in parallel. If this closing up of the brushes were to take place, then, when the armature is in the position shown in the figure, the comparatively inactive coil B would be disconnected, and A and C joined to the external circuit in series. The maximum E.M.F. would be developed when each pair of brushes is so closed up as to form practically one brush, in which case the least active coil would be always out of circuit and the other two joined up in series. From this point any opening of the brushes puts two of the coils in parallel for a greater or less interval of time, and reduces the E.M.F. actually developed; therefore when the current becomes abnormally strong, the brushes are opened until the E.M.F., and, consequently also, the current, are reduced to the normal value. The motion given to the brush-holders by the regulator is such that the following brush of each pair travels three times as fast as the leading brush.

The brushes *d*, *e*, *f*, *g*, are mounted on a double lever, having a scissors-like movement about a common centre. The end of the lever carrying the brushes *d* and *f* is connected by the bar H to the armature K, under the electro-magnet M. This armature is hinged at L, and when the current in the main circuit becomes excessive, K is attracted, *d* and *f* are drawn back over the commutator, while *e* and *g* are pushed forward by a simple combination of levers not shown in the figure. The electro-magnet M and the double solenoid P are both in the main circuit with the field-magnets F F and the lamps G; but normally M is short-circuited by wires whose circuit may be broken at *x y*. The contact *x* is attached to the yoke of the two cores of the solenoids, and the first effect of an increase in the current is to raise the cores, break the contact at *x y*, and so cause the whole of the current to pass through M, which then attracts K and opens the brushes. A high resistance carbon shunt is inserted at S to minimise the spark at *xy*. It will be noticed that the end of the core of M is shaped somewhat peculiarly and fits into a corresponding cavity in the armature; this shape is calculated to diminish the force of attraction uniformly as the armature recedes from the core. The regulating apparatus is shown in position in fig. 215. The small cylinder to the right of the electro-magnet is a dash-pot for steadying the movements of the lever.

FIG. 219.



There is one other device pertaining to the Thomson-Houston to which a reference is necessary, and which is employed to suppress the excessive sparking caused by cutting out the coils when fairly active and which would otherwise speedily destroy the commutator. The segments are separated by air-spaces, and just in front of each leading brush is placed a nozzle which delivers a strong blast of air at the moment that the brush breaks contact, and so actually blows out the spark. The automatic 'blower' by which these timely puffs are delivered is shown in section in fig. 219. A circular steel hub, H, is keyed on to the shaft, X, and revolves left-handedly in an elliptical chamber in the fixed box T T. Air enters this chamber through the apertures at *i i*, which are protected by wire-gauze coverings. The hub H is provided with three radial slots, in and out of which the rectangular ebonite slips can slide freely. As the shaft rotates these slips fly outwards by centrifugal force, and, pressing continually against the walls of the chamber, force the air in front of them and out at the holes *a a*, to each of which is connected one of the two nozzles above referred to. The chamber is fixed to the framework of the machine in the necessary position for the maximum force of the blast to take place at the right moment. O is a vessel from which oil passes into the elliptical chamber through the aperture *i*.

The machine illustrated is designed to supply a current of about 9½ amperes to 34 arc-lamps in series. The armature is 2 feet in diameter, over all, and the resistance of the field-magnets and of the armature is in each case 10½ ohms.

In addition to the dynamos which have been described in this and the preceding chapters, there are many others to which the scope of this work has not permitted us to refer, although some of them are well worthy of study. We believe, however, that quite enough has been said to give the student a good insight into the science of dynamo-building as it is now practised. Where we have given sectional views or working drawings, they have for the most part been specially prepared for this work and refer to machines manufactured since the summer of 1889.

A comparison of these chapters with works of a similar character published a few years ago, will show that the modern trend in dynamo design is towards simplification and uniformity of detail. As an example of the latter, we may cite the construction of commutators, in which the materials now employed are nearly always exactly alike, while in the manner of building up the parts so as to prevent the sections flying out, there is very little real difference to be found. This similarity is what might, perhaps, be anticipated, for if the vast number of experiments which have been performed by the various manufacturers to determine which is the best appliance to perform a given kind of work, have been equally exhaustive and accurate, an almost identical result should have been arrived at. Thus, no metal has been found superior to hard-drawn copper for the bars of a commutator, while for the extremely difficult task of satisfactorily insulating these bars in the case of a closed-coil commutator, nothing has been discovered which approaches mica ; indeed, were this mineral not available, it is probable that some alteration would have had to be effected in the general design.

Great things were at one time expected of asbestos for insulating purposes, but it proved to be a good absorbent of oil and was charred by the sparking, while the adhesion of metallic particles abraded from the bars and brushes soon developed a greater or less amount of short-circuiting with its concomitant evils. A somewhat similar result attended the use of simple air-spaces for insulating the bars, for the metallic dust or scrapings accumulated sooner or later at the bottom of the spaces, which, being numerous, were necessarily narrow. Occasionally a special form is given to a commutator; for instance, that of the small exciter shown in fig. 134 is built against the end of the armature, the individual bars being disposed radially. The object here is to reduce the length of the machine. A special commutator is also employed with the machine illustrated in fig. 221, the object of which is explained in the description.

Again, the lamination of the core of an ordinary cylinder or of a drum armature is a matter upon which little doubt now exists, for it is as certain as it well can be that the magnetic resistance should be kept as low as practicable, a result only to be arrived at by retaining metallic continuity in the direction of the lines of force and using extremely thin insulation; while, on the other hand, the lamination must be carried far enough to sufficiently reduce the eddy currents. Nothing better, therefore, can be devised than a core of thin iron plates of high permeability, separated by the thinnest possible layer of insulating material, the only doubtful point being the thickness of the plates. Such experiments as those referred to at the end of the preceding chapter may help to decide this point, and it is just possible that by this means some further knowledge may eventually be gained which will enable the other losses in the core to be minimised.

With regard to the closed-coil armatures it is probable that the cylinder or ring form will in the future be even less frequently employed than it is now, the drum type with a simple field, and the flat disc with a multipolar field, having been proved to possess so many important advantages. Thus, again, we see that the result of experience is to reduce the number of types to one or two distinctive ones, whereas a few years ago almost every individual machine might be said to be of a class peculiar to itself.

Indeed, the principal difference now apparent in the construction of dynamos is in the form and arrangement of the field-magnets, and these matters are frequently determined by local circumstances. For example, one maker may have tools capable of doing a class of work altogether out of the question at another factory. Or, again, the question of weight may have to be taken into account, dictating the use of wrought-iron where otherwise cast-iron would be the more economical.

The theoretical form of field-magnet, circular in section (so as to require the minimum amount of wire), and made of soft iron without molecular discontinuity, is too expensive and inconvenient to be rigidly followed, especially in large machines. Equally powerful fields can be produced with rather more copper wire and a little greater expenditure of power in the field-magnet coils by the use, partially or entirely, of cast-iron, with close-fitting joints.

The great variety in the form of field-magnets is also largely due to the difference in the views of the various makers as to the method of obtaining the most economical construction. Very few now manufacture dynamos with the armature at the lower extremities of a pair of vertical field-magnets, where slabs of zinc or frames of gun-metal have to be interposed between the pole-pieces and the iron bed-plate, to reduce the magnetic leakage. Sometimes this type is adopted in order to economise space and make the machine as squat or short as possible, three coils being then wound on the field-magnet, one on each leg and the third on what we are accustomed to call the yoke.

The purpose for which dynamos are most frequently designed is to light a number of incandescent lamps joined up in parallel circuit. It is necessary to maintain a constant potential difference at the terminals of these lamps, say of 110 volts, and consequently the machine employed should be shunt-wound, with a very low resistance in the armature ; or, if the number of lamps is likely to be subject to considerable variation, the machine must be compound-wound. For the important work of 'charging' secondary batteries, a simple shunt-wound machine is the most suitable. A series dynamo is, of course, capable of performing this work, but it requires to be used with extreme care, because as the electro-motive force of the cells rises, its opposition to that of the machine becomes more pronounced and the current falls in value. The polarity of the field-magnets may, indeed, be eventually reversed, when the current from the cells will drive the machine as a motor. On the other hand, when using the shunt-machine the electro-motive force of the cells tends to increase the current passing through the field coils, whence the danger of reversal is diminished.

Many dynamos are now employed for the deposition of metals, electroplating, &c., and for this purpose they are required to furnish very heavy currents at a low potential difference. They are frequently series-wound and it is necessary that the internal resistance should be extremely low, otherwise considerable power would be wasted by the passage of the currents, which sometimes exceed 1,000 amperes. To obtain this low resistance a drum armature may be constructed with very massive bars for the active conductors, the field-magnet coils consisting of a few convolutions of massive copper band. An electro-motive force of from six to eight volts is usually ample, and this, notwithstanding that there are but comparatively few active conductors round the armature, can be obtained without the necessity for driving at a high speed. But it is not an easy matter to secure these massive bars, and consequently many machines are made with a number of fairly thick wires joined up in parallel to form one conductor. In order to reduce as far as possible the loss of energy at the commutator it is essential that the brushes should be large, and the amount of contact surface considerable. A large machine, somewhat similar in appearance to that depicted in fig. 185, has been constructed for electro-deposition work; it develops the comparatively high E.M.F. of 50 volts, and can yield 1,000 amperes at a speed of 350 revolutions.

Multipolar machines, as has already been indicated, afford a means of easily securing mechanical strength with extremely low resistance.

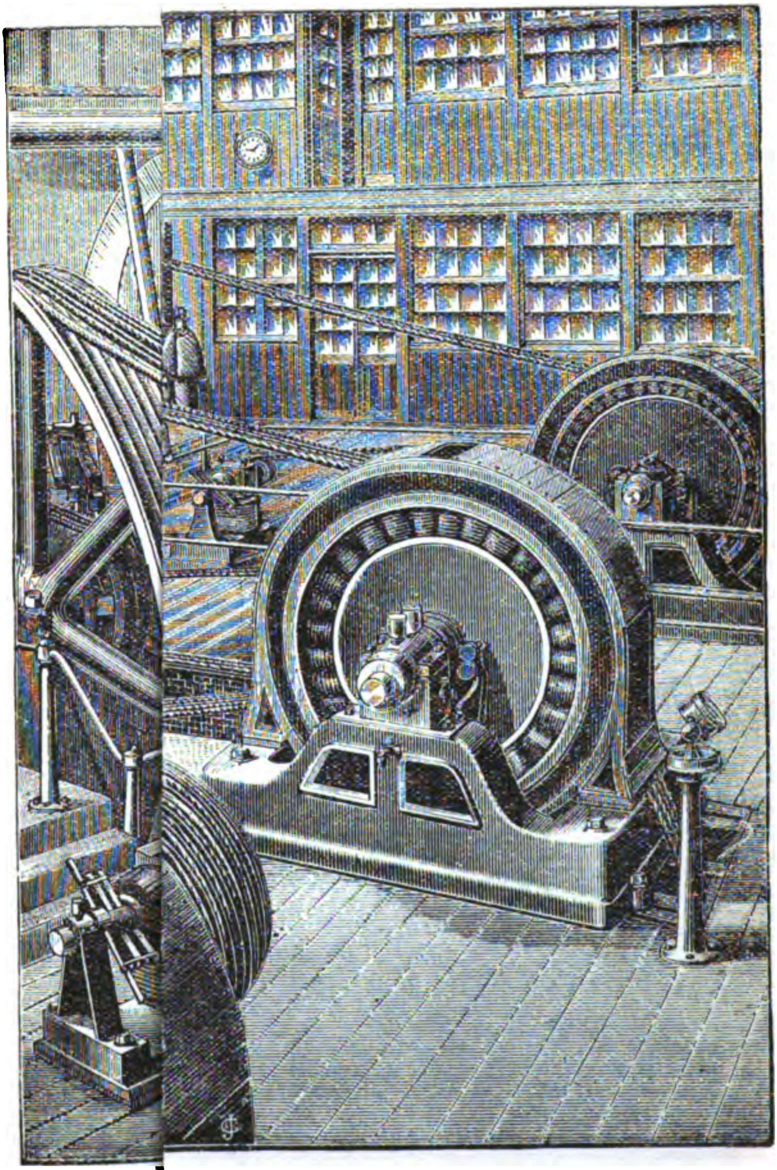
For supplying current to a number of pieces of apparatus joined up in series, whether arc-lamps, low-resistance incandescent lamps, or motors, it is necessary to maintain a constant current under all conditions. The two open-coil machines described in this chapter, and the dynamo illustrated in fig. 194, are suitable for this class of work.

CHAPTER XII.

MOTORS AND THEIR APPLICATIONS.

We must now give some attention to the important class of dynamo-electric machines employed for the purpose of converting, at any desired point, energy supplied to the machine in the form of electricity, into energy in the form of mechanical motion.

In its widest sense this conversion rests upon the fact that whenever any of the lines of force forming part of two separately generated magnetic fields traverse a common space, there is a decided action between the two sets of lines, the tendency being to so alter their paths that as many lines as possible shall coincide in direction. By bearing in mind this simple general rule, little difficulty should be experienced in predicting the results which will follow, even in complicated cases. This mutual action takes place independently of the means by which the fields are developed, whether by currents in two wires (straight or coiled, with or without cores), or by permanent magnets ; or, the one field by a current in a wire and the other by a magnet. In the effort to make the coincidence a maximum, both fields are distorted from the configuration which they would independently have retained, and this configuration is again assumed immediately they are removed from each other's influence. Consequently, when the lines of force pertaining to two fields approach each other, their mutual action sets up a stress, the effect of which is a tendency to impart such a motion to the material substances (whether a steel bar or a conducting wire), employed in generating the fields, as to make them take up positions in which the lines of force due to both fields coincide to the greatest possible extent. The stronger the fields, the greater is the force thus acting, and, if sufficiently strong, mechanical motion is imparted to that body which moves



(To face page 402.)

the more freely. For instance, suppose one field to be a simple one developed between the two pole-pieces of a powerful field-magnet such as has been described, and the other field to be generated by a current in a circular loop of wire. If the loop is placed vertically with its edges towards the pole-pieces, that is, with its plane parallel to the lines of force of the field-magnet, then the lines of its own field will be projected at right angles to those of the other, and the field-magnets being too massive to move, the loop will, if freely suspended, immediately turn round through 90°, when the lines of force of the other field thread through it in the same direction as its own lines. If free to move in any direction, its ultimate position of rest will be in the densest portion of the field, where the number of lines passing through it, and coinciding in direction with its own lines, is a maximum. If the current through the loop is then reversed in direction, it will turn completely round until the lines of both fields again coincide.

We have thus a means of imparting mechanical motion to a material substance, in this case a loop of wire ; and a continual rotatory motion can be maintained by reversing the current in the loop at the right moment, viz. just when its momentum has carried it a little beyond the point which, in the absence of this reversal, would be its position of rest. It remains to be seen how the principle is practically applied, on a scale such that the force with which the movable body is urged into a new position may amount to many horse-power.

Referring to the simple case of a closed-coil armature with a two-part commutator, as illustrated in fig. 149, it will be observed that if a current is sent through the two coils in parallel, while in the position shown, no movement results when the direction of the current is such that the lines of force due to it coincide in direction with those of the fixed field. This is the position of rest for the armature, and if the current in it is reversed, it will make a complete revolution until the same coincidence again exists. Now the current can be supplied by brushes pressing on the commutator segments, and so placed that each segment slides into contact with a fresh brush directly the position of rest is arrived at. By this means the current will be reversed, and a continuous rotation kept up. With only two coils, the armature might come to rest suddenly at a dead point and would not start again from such a position: but the number of coils can be increased with advantage until we have, practically, an armature similar to those used in generators. On a current being sent through such an armature, each coil strives to set itself with its plane at right angles to the field, in which position the coincidence of the two sets of lines is at a maximum. Immediately the coil arrives at this point, the current in it is reversed, causing it to exert a similar force in the same circular direction, during another half revolution.

The armature may be of the ring, drum, or flat-disc type, and it fortunately happens that most of the principles underlying the design and construction of a good generating dynamo, hold equally well for a motor. The fixed field is usually supplied by powerful electro-magnets as in the case of generators, these being excited by a current from the same source as that which supplies the armature. Many of the troubles which in dynamos are avoided or reduced by the employment of a fixed field sufficiently strong to overpower that developed by the armature, are also inherent in a motor, and may be avoided by the same arrangement. But in a motor the question of weight is frequently of considerable importance. For instance, the machine may be employed for the purpose of propelling a vehicle, and in such cases the weight of the motor is added to that of the vehicle, and involves a proportionally increased expenditure of power in moving it. Again, in constructing a motor, even more care must be exercised than with a dynamo, in rendering the armature able to resist sudden heavy stresses without risk of damage, the reason for which will be more apparent presently.

We have already learned that when a conductor moves through a magnetic field in such a manner that it cuts the lines of force transversely, an E.M.F. is induced in the wire, this E.M.F. depending upon the density of the field and the velocity of the wire; the cause which sets the wire in motion being quite immaterial. And if an independent current is already flowing in the wire, the electro-motive force induced by the motion, will either tend to increase or decrease this current, according to its direction. Now when a wire, free to move, is placed in a certain position in a magnetic field, and a current is sent through it, it quickly moves to a new position. But in the very act of moving across the field, the wire cuts the lines of force, and an electro-motive force is consequently induced in it. As such reactions always tend to stop the motion of the moving body, and as any reduction in the current must necessarily reduce the force with which the wire is moved (by the mutual action between the fields), the induced E.M.F. must oppose and reduce the current which is flowing.

In consequence of this 'counter-electromotive-force,' the current which a given external source of E.M.F. can send through a motor, varies with the speed at which the wire of the movable part of the machine is at the moment cutting the lines of force of the field. When the revolving part is forcibly restrained from moving, the current is at its maximum, being simply the quotient of the E.M.F. divided by the resistance. But when it is allowed to move, the current immediately falls in value, and the higher the speed, the feebler is the strength of the current. This may be observed experimentally by placing an ammeter in circuit with a battery and a motor, and then varying the speed of the latter.

Now, any one of the dynamos hitherto described can be used as a motor. For instance, we may take a direct current series-wound machine, and, by simply passing a current through it from a battery of secondary cells, can cause the armature to rotate rapidly. The force with which the armature moves, depends upon the strength of the fields produced by it and by the field-magnet, and these in their turn depend upon the strength of the current.

The internal resistance of a secondary battery is very low, and if that of the machine is also low, an enormous current will pass while the armature is at rest; sufficiently strong, if maintained for any length of time, to damage it. But immediately the armature begins to move, this enormous current falls, until presently the speed of rotation and the counter-electromotive-force may become so high that only a very small current can flow, the force with which the armature turns, or the torque,[1] being, of course, also considerably reduced. This variation is extremely convenient in some cases; for example, when a motor is employed to propel a tram-car, it is required to exert very much greater power to start the car from rest, than to keep it in motion after it has been started. It is just when the car and the armature of the machine are at rest, that an enormous current can be sent through the machine, and a correspondingly great power exerted on the shaft; while the current falls to a safe value when a start has been effected, and before any damage can be done to the machine by over-heating. The necessity for its being able to resist such sudden heavy stresses as that caused by the effort to start with a heavy load, requires exceptional care to be exercised in the mechanical construction of a motor armature. Special attention is here directed to the machine illustrated in fig. 189; in which the armature conductor lies in deep narrow slots in the core, every plate of which bears directly against the shaft, the whole construction being such as to render the armature able to withstand an enormous torque without injury.

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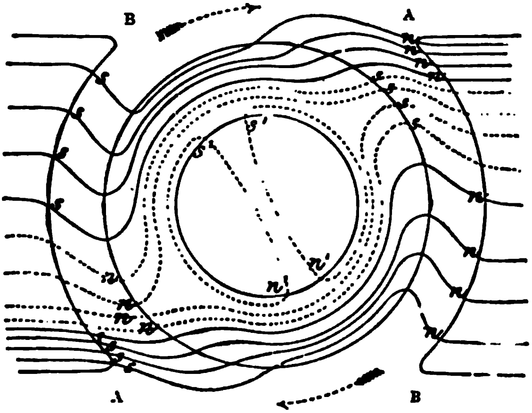
[1] The 'torque' is the moment of the force which tends to cause rotation. In this case it is equal to the length of the arm, that is, the radius of the armature, multiplied by the pull at the circumference on the conductor.

Supposing the field to be unaltered, the direction of the current in the armature of a machine when used as a motor, must be the reverse to its direction when used as a generator, if the direction of rotation is desired to be the same in each case; indeed, we have just seen that the counter-E.M.F. generated is opposite to that which produces the driving current. Therefore, if the direction of the driving current is the same as that which would be developed by the machine itself, the connections of the armature or of the field-magnets of a series dynamo must be reversed; or if a rotation in the opposite direction is desired, the connections should be left unaltered, and the brushes turned round to suit the reversed rotation. A shunt dynamo, on the other hand, will, without any alteration, turn in the same direction if an E.M.F. opposite to that developed by it as a generator is applied to its terminals, for the current through the armature is then in the reverse direction, while that through the field-magnet coils is the same as before. This will be apparent on inspection of the diagrams of the shunt dynamo connections given in figs. 159 and 160; when employed as a generator the field-magnet coils form a shunt to the external circuit, but when used as a motor these coils act as a shunt to the armature.

The distortion of the field observed when a machine is used as a generator also occurs when it is employed as a motor, because, when the brushes are at zero, the lines of force of the armature field are at right angles to those of the field-magnets. But the direction of the current, and therefore of the lines of force, being reversed in the case of a motor armature, the direction of the resultant field is also different. The amount of the distortion depends, obviously, upon the relative strengths of the two fields. It is very slight when the field-magnets overpower the armature, but in all cases the direction of the resultant field is such that the brushes must be shifted *backward* to place them on a diameter at right angles to the lines of force, and so to avoid sparking.

The distortion of the field of a motor is illustrated in fig. 220, which should be compared with the corresponding figure (156) for a generator. The density of the lines of force is greater at the horns A A which the armature is approaching, and, as a consequence, any irregular distribution of iron in the armature core causes stronger eddy currents and develops more heat at these places, than at the horns B B from which the armature is receding, as in the case of a dynamo. With an ordinary armature, however, this heating is not very great, and in all cases it is influenced to a certain extent by the fact that a current of cold air is drawn in at

FIG. 220.



A A and ejected somewhat warmer at B B. In the case of a motor, therefore, this air current tends to reduce, and in the case of a generator to increase, the difference of temperature between the two horns of each pole-piece.

The current through the armature of a motor frequently varies considerably, and this may cause a shifting of the resultant field, and therefore also necessitate an alteration in the position of the brushes, but in all cases a reduction in the angle of lead, and immunity from sparking with a variation of the armature current, may be obtained by employing a very powerful field relatively to that produced by the armature. But this necessitates considerable weight, especially in the field-magnet cores. Hence, the superiority of wrought-iron of high permeability is apparent, although even when this is used the weight of a motor built upon this principle is still considerable. As we shall see presently, the most effective plan of constructing a light but efficient machine is to arrange that the armature field shall be very powerful and reinforce that of the field-magnets, special precautions being taken to prevent the sparking which would otherwise ensue. But at the same time it must be remembered that the advantages accruing to the use of powerful field-magnets, even at the expense of extra weight, are not lightly to be thrown away; and that in ordinary cases it is rarely true economy to sacrifice much in order to save a little weight.

The electrical power may be supplied either at a constant pressure, or constant current; in the former case regulation is comparatively easy, while in the latter greater economy in the distribution of power can sometimes be effected. Supposing a constant potential to be maintained at the terminals of a shunt-wound motor; the current through the field-magnet coils will always be the same, and therefore the strength of the field remains constant, but the current through the armature depends upon the speed of rotation, being, in fact, determined by the excess of the applied electro-motive force over the counter-electro-motive force. Supposing the machine to be employed in driving a tram-car; then, for example, when the car commences to mount an incline, the armature shaft is called upon to perform additional work, which tends to reduce the speed of rotation; this, however, by reducing the counter-electro-motive force, immediately allows a stronger current to pass through the armature, and affords the necessary electrical power to perform the extra work. On the other hand, should the car be allowed to attain a high speed in descending an incline, the counter-E.M.F. would reach a high value, so high in fact that very little current would pass through the armature, whence very little electrical power would be expended. The demand upon the source of the electrical power is thus to a certain extent automatically regulated in a very simple manner according to the requirements, and this effect of the counter-electro-motive force obtains, whatever the purpose may be for which the machine is employed.

If the armature resistance is extremely low and that of the shunt-coils high, and if the field-magnet develops a much greater field than the armature, the variation of lead will be but slight, and further, the machine will to a great extent be self-regulating as regards speed. But since these conditions are not always obtained in a motor to the same extent as in a dynamo, chiefly on account of the anxiety to reduce the weight, few shunt motors are sufficiently self-regulating to meet all requirements. We have seen that when an additional load is thrown on the motor, the resulting reduction in speed immediately allows the passage of a stronger current through the armature; but if the speed is to be kept constant, the counter-electro-motive force also will be constant, and then the current through the armature can hardly vary at all, so that the two conditions are opposed to each other. But by reducing the strength of the field developed by the field-magnets, the counter-E.M.F. can also be reduced, and therefore a stronger current can be passed through the armature when rotating at a given speed. It is necessary, then, to devise some means of reducing the strength of the field when the load is increased and the current in the armature rises. The simplest way of accomplishing this is to place a few turns of thick wire round the limbs of the field-magnet, in series with the armature, but wound in such a manner as to magnetically oppose the shunt-coils instead of assisting them, as in the case of a compound-wound generator. The effect of these series-turns in weakening the field becomes greatest when the armature current is strongest, and *vice versâ*; but it should be observed that since the strongest current which can pass through the armature does so when it is at rest, the armature may start in either direction as determined by the shunt-coil field, or the field produced by the heavy current in the series-windings. To avoid any uncertainty, it is usual to lead the ends of the two windings and of the armature separately to the switch-board, and to reverse the current through the series-windings, so that both shunt- and series-coils act together in developing a strong field at the moment of starting, the series-turns being joined up in the normal manner when the speed rises above a certain value.

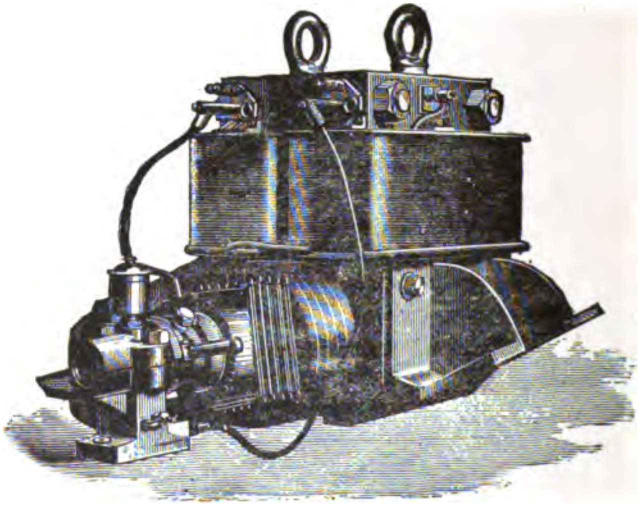
The field of a shunt motor may also be weakened by inserting resistance-coils as required, either by hand or automatically, or by altering the ampere-turns in any other manner. It appears at first sight somewhat paradoxical that the speed of a motor can be increased by reducing the strength of the field, but the reduction of the counter-electro-motive force of the armature, as mentioned above, satisfactorily explains the matter. The case for a series motor fed with a constant current is different, and the distinction must be clearly borne in mind. If the load is decreased, the speed increases, and so gives rise to a higher counter-E.M.F., but the generator responds to this and maintains the current constant. Consequently the speed of the machine increases enormously when the load is lightened to a great extent, and it is then that unless care is taken considerable damage may be done. The weakening of the field of a series motor reduces the power given out, and therefore, also, reduces the speed if the load and the current through the armature are unaltered. The alteration in the strength of the field is conveniently effected by shunting the field-magnet with a variable resistance, and the application of one such method will be considered presently. We shall also refer to the manner in which highly successful results have been achieved by means of series motors supplied at a constant potential.

Only a portion of the power given electrically to a motor is converted usefully into mechanical power, a part being spent in heating the armature, field-magnet coils, &c. When the armature is at rest the whole of the electrical power absorbed by the motor is so converted into heat, and the efficiency of the machine, that is, the ratio of the useful power obtained on the shaft to the total power supplied, is at its lowest value, viz. nought. When the armature is moved, the useful performance of work begins, and as the current also falls in strength, the power wasted in heating decreases. The higher the speed of rotation, the higher becomes the counter-E.M.F., and the less becomes the power wasted as heat in the conductors; in fact, the ratio of the power usefully absorbed by the motor to the whole power supplied, is very nearly proportional to the ratio of the counter-E.M.F., to the E.M.F. applied at the terminals of the machine. The efficiency of the machine is therefore highest when the load is a minimum, that is, when it is doing least work per revolution, while the torque, or the force with which the armature tends to rotate, is greatest when the load is sufficiently great to prevent the armature turning, and when, therefore, it is doing no external work at all. Now when a motor is running at a high speed it performs very little work indeed during one revolution, although, the number of revolutions being great, a considerable amount of work may be performed during a given interval of time, say one minute. On the other hand, when the speed is very low, the amount of work per revolution is comparatively great, but the small number of revolutions per minute prevents the quantity of work reaching during that interval a very high value. By considering these two extreme cases, it might be supposed that there is a certain intermediate speed of rotation at which the work performed by any given motor is a maximum. This is the case, and the speed of a motor at which it can perform the maximum amount of work per minute is that speed at which the counter-electro-motive force becomes equal to the electro-motive force applied at the terminals. This result is quite independent of the *efficiency* of the conversion, which, as we have seen, increases with the speed of rotation.

In fig. 221 is illustrated a motor which was constructed by Messrs. Goolden for an electric launch. The field-magnet is of the single horse-shoe shape, the cores being of wrought-iron, secured to a wrought-iron yoke-piece by two horizontal bolts. On the outer side of each pole-piece is a gun-metal supporting bracket with two flanges, shaped to fit the ribs of the boat. One bracket (that at the back in the figure) is extended on either side to form the bearings for the armature shaft.

The machine is shunt-wound, the field-magnet coils consisting of 2,680 convolutions of No. 14 S.W.G., having a resistance of 6·96 ohms. The armature is of the drum type, and is wound with two No. 14 S.W.G. wires in parallel, there being 216 convolutions of this double wire, giving a resistance from brush to brush of 0·2 ohm. Each section has six turns, so that there are thirty-six bars in the commutator, which is insulated throughout with mica. The adjacent end of the armature is covered by radial extensions of the commutator bars, the mica insulation being also extended to the periphery. The other end of the armature is covered by a metal plate of an equal diameter, the rest of the armature being enveloped by a waterproof material securely banded on, so that the whole is rendered completely watertight. The armature shaft is, at the end remote from the commutator, coupled direct on to the shaft of the propeller. The armature brushes and field-magnet coils are connected to separate terminals leading to the controlling switch, and the motor is reversed by simply reversing the direction of the current through the armature. To render this practicable, the brushes are of a special type (see fig. 227),

FIG. 221.



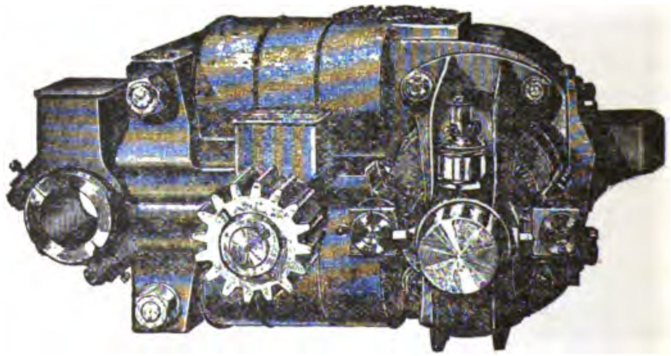
consisting of steel springs placed flat against the commutator, and provided with solid carbon blocks for making contact, the requisite pressure being given by india-rubber bands passing round hooks at the ends of the springs. This motor develops five horse-power when running at 500 revolutions per minute: the current is supplied by secondary cells, the machine being designed to carry 50 amperes at 95 volts, but the margin is such that it can safely take up to 70 amperes for several hours without risk of damage by over-heating.

The efficiency of this motor is about 85 per cent., which is high for so comparatively low a speed as 500 revolutions per minute. In most cases the difficulty of obtaining a machine of reasonable efficiency at a low speed, without abnormal proportions and correspondingly heavy weight, renders it necessary to run at a high speed, and to effect the reduction required, by suitable, gearing. Thus, for example, the wheel of an ordinary tram-car travelling at seven miles per hour does not revolve at so high a speed as eighty revolutions per minute, and it would be impossible to construct a practical motor to run at this low rate. A machine running at 720 revolutions might be employed, by introducing gearing which would reduce this speed to about one-tenth. The selection of suitable gearing is not, however, an easy matter, for it must be light, strong, and durable, and should produce neither noise nor vibration in working; and, while absorbing little power in friction, it must be capable of withstanding dust and dirt, or of being easily protected. Some very good devices, depending upon friction to transmit the power from a small wheel on the rapidly rotating armature shaft to a larger pulley on the axle, have been employed with fair success on lines where the gradients slight; but where the power required to be transmitted is at times very heavy, this method is not to be relied on. By means of a pinion and spur-wheel, with or without an intermediate counter-shaft, very great power can be transmitted. One principal objection to this gearing is that it is noisy; the teeth of the pinion on the armature shaft also rapidly show signs of wear.

The necessary reduction in speed can also be obtained, and in a very satisfactory manner, by means of a screw and worm-wheel; an endless screw, driven by the motor shaft, gearing into the teeth of a worm-wheel on the axle of the car or on a countershaft. Chain gearing is also employed; in this case an endless chain passes over a small toothed wheel on the motor shaft and a larger one on the axle, the teeth of the wheels fitting into the links of the chain. The chain is, however, liable to stretch, and then the teeth no longer fit accurately, and slipping is likely to take place.

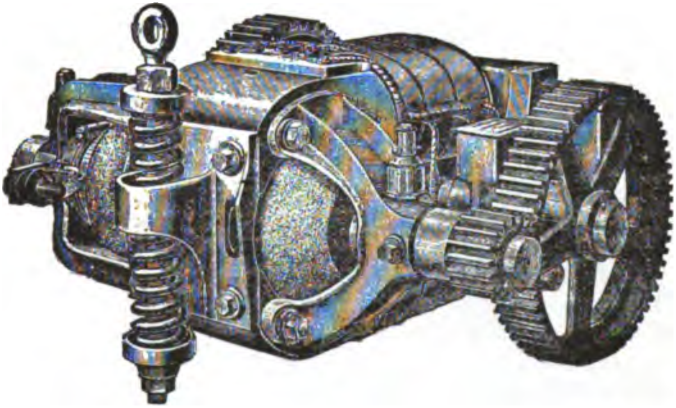
In figs. 222 and 223 a good example of spur-gearing is illustrated. The motor, designed by Lieut. Sprague, is intended for use on a tram-car, the field-magnet being of the single horse-shoe type, and of wrought-iron throughout. At the yoke end, the motor is swung from the axle of the car, this bearing being shown to the left of fig. 222, while at the other or armature end, it is flexibly supported, being attached to the body of the car by means of the spring shown in fig. 223. Bronze brackets, fixed to the pole-cheeks, support the armature bearings, and a pinion on the armature shaft, as indicated in fig. 223, gears with a spur-wheel carried on a counter-shaft which passes between the limbs of the field-magnet. At the other end of the counter-shaft is the pinion, visible in fig. 222, which gears into a spur-wheel keyed on to the axle of the car, the number of teeth being so proportioned, that the speed of rotation of the axle is about one-twelfth of that of the armature.

FIG. 222.



The pinion on the armature shaft is sometimes made of hard vulcanised fibre. The wear is, of course, greatest at the teeth of this pinion, while the greatest power is transmitted by the teeth at the other end of the train. The teeth are, however, strong enough to resist a *steady* pressure far greater than can be given by the machine; were the full power suddenly applied with a jerk, the strain would be enormously increased, but a most important function of the supporting spring is to prevent this taking place, by yielding slightly when the pressure is suddenly applied. But the advantage gained in this way entails the disadvantage that the distance between the centres of the engaging wheels is liable to variation. Consequently, involute teeth are employed, that is to say, the form of the rubbing surfaces of the teeth is the involute of a circle, such teeth being the only ones which are independent of an alteration in the distance between the centres of the wheels.

FIG. 223.



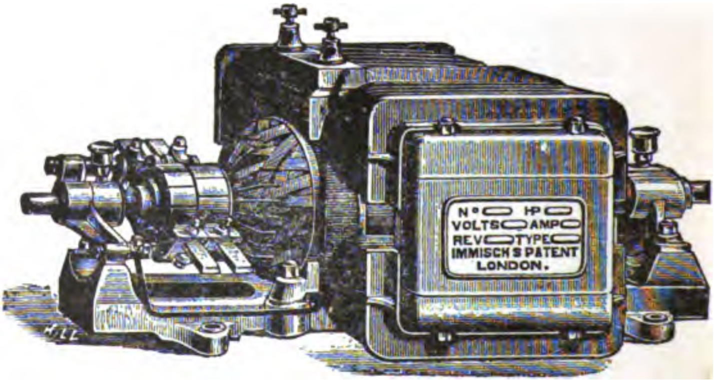
The armature is entirely covered with a waterproof material, and the field-magnets being also protected by an impervious covering, the machine is but little liable to injury from moisture.

The covering of the field-magnets consists of sheet copper, the joints being carefully sealed. An advantage attending this arrangement is, that the heavy current induced in the low resistance copper sheathing reduces to a very great extent the magni tude of the extra current developed in the coils on suddenly breaking the circuit.

Carbon brushes are employed, the commutator being of the usual form, viz. copper bars insulated with mica.

In fig. 224 is illustrated the Immisch motor, a type which is in extensive use, and possesses some important peculiarities. The field-magnets are of the double horse-shoe form, the coils being wound in four sections on the horizontal portions of the core, although in a few instances two coils are employed, wound on the vertical limbs, as in the case of the Manchester dynamo.

FIG. 224.



In these machines the magnetic field developed by the armature is comparatively powerful, being equal to, or even greater than, that developed by the field-magnet, the object being to effect a great reduction in weight. As has been already remarked, it is possible, since the two fields reinforce each other, to employ a weak fixed field and yet obtain the necessary torque on the armature, provided the armature field is correspondingly increased in strength; but this entails some special device to avoid the necessity for altering the lead of the brushes to suit the variations of the current caused by a varying load. The actual requirement is, of course, to keep the direction of the resultant field unaltered, so that the brushes shall always be on a diameter at right angles to this field; and in the Immisch machine the arrangement for maintaining this constancy amounts to simply short-circuiting the sections of the armature for a considerable period as they pass the neutral position. If the field is in its normal position when these coils are short-circuited, they are practically inactive. But should the field be shifted, say by an increase of the load, the short-circuited coils cut lines of force transversely, acting as the coils of a generator, and the resistance of the closed coil being very low, the conditions for a large current are established, the lines of force resulting from it being in such a direction as to oppose the distortion of the field, and bring it back to the normal position. The short-circuiting is effected by the commutator, which, as shown in fig. 224, consists of two sets of segments, placed side by side, one set being fixed half the width of a segment in advance of the other.

The armature is drum-wound, and the connections are such that the two parts of the commutator might be formed into one, by interposing each segment on one half between the two facing segments on the other half. The two brushes, side by side, are electrically connected, forming, in fact, one wide brush, and the effect is precisely similar to what would take place if an ordinary commutator were employed with thick brushes covering one bar.

Under ordinary circumstances the effect of an increase of the current in the armature would be to increase the distortion of the field, and therefore to necessitate a greater negative lead being given to the brushes. The immediate effect, however, in the present case is to cause the short-circuited coils to generate a powerful current, the lines of force due to which are in the same direction as those of the field-magnets, the resultant tendency being to reduce the distortion to its normal amount.

It might be expected that considerable heating in the coils would result from the short-circuiting, but this does not occur to any appreciable extent, and is probably to be accounted for by the prompt action of the current in the short-circuited coils in restoring the field to its normal position before the current rises to a very high value.

The armature core is built up with the usual thin iron plates, which are insulated with asbestos, thick rigid plates being placed at intervals, and having projections above the surface of the rest of the core, which act as driving horns.

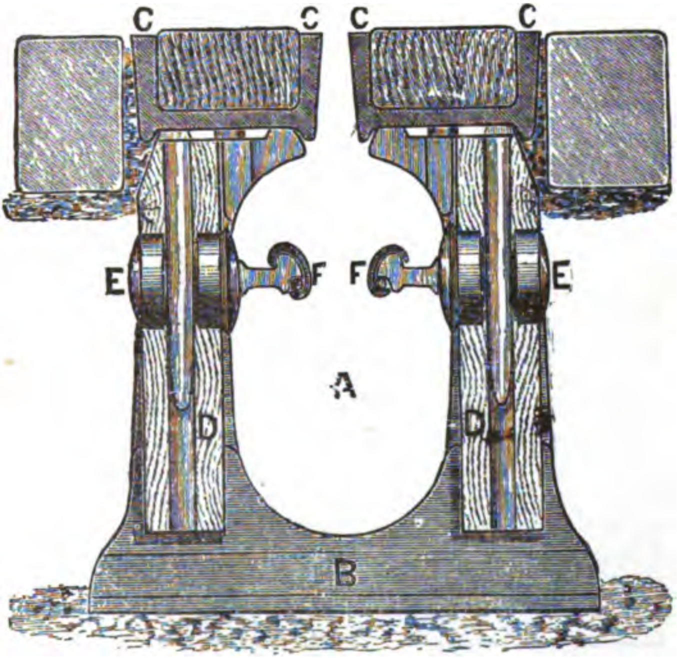
The machines are usually series-wound, and are made in a variety of sizes for different purposes. One, designed for driving a tram-car, weighs 5½ cwt., and is intended to run at 1,000 revolutions with a current of 40 amperes at 60 volts. The gearing consists of two steel chains with a counter-shaft, the reduction of speed being 10 to 1; the velocity of the chain on the armature shaft is, at times, as high as 2,000 feet per minute, the high speed of the motor allowing a considerable reduction in the weight of the machine. The current is supplied by eighty secondary cells carried on the car, a switch being provided for connecting these, all in series, or forty in series and two in parallel, so as to vary the power given to the machine. The same switch can also be used to throw resistance in circuit, when the motor is being started, to prevent the passage of a too heavy current. The direction of rotation is reversed by reversing the current through the armature, two sets of brushes being provided, operated by a suitable lever, one set adjusted with a slight negative lead in one direction, and the other set with a corresponding lead in the reverse direction.

One of the earliest and most successful applications of the electric motor was made by Mr. M. Holroyd Smith, on the Blackpool Electric Tramway. This venture was made in the experimental days of electric traction, and great difficulties have been contended with and overcome. The working has been so successful under somewhat trying local conditions as to prove that the system is sound, and we shall accordingly briefly describe the main features. The line is two miles in length, and consists chiefly of a single track with a number of pass-byes. It runs along the sea-coast in such an exposed position that the road is occasionally flooded during the winter months, and at all times the saline deposit, which is always prevalent near the coast, considerably enhances the difficulty in insulating the conductors.

The conductors are laid underground in a channel midway between the two rails on which the car wheels run, the current being taken from them to the motor, by means of a collector trailing through a narrow opening in the top of the channel.

In fig. 225 a transverse section of this channel is shown, the main support being afforded by cast-iron chairs which are fixed at intervals of a yard. One of these chairs, B, is shown in the figure; its height is 11 inches, base 12½ inches, and internal width 5½ inches; it has vertical slots cast in it, on each side, and into these slots are fitted stout creosoted boards, D D, which form the sides of the channel. Steel troughing, C C, runs along and is bolted to the tops of the cast-iron chairs. This troughing is then filled with wooden blocks to form the paving of the road; the remainder of the paving being also of wood. The sides of the steel troughs slope slightly, so that the opening between them widens from half an inch at the top to one inch at the bottom, in order that a stone may fall through instead of being wedged in. The conductors are strips of hard-drawn copper, of the shape shown at F F; the sectional area of each is equal to a solid rod 0·575 inch in

FIG. 225.



diameter, and its resistance is 0·165 ohm per mile. The strip fits over an iron stud, the under side of which is grooved, and a wooden pin is driven in, to fix it securely in position. This stud is cemented into a cylindrical porcelain insulator, E, having a deep groove round its periphery, and holes 2½ inches in diameter are bored in the wooden sides of the channel midway between the chairs, for the reception of these insulators. A ¾-inch vertical hole is also bored in the wood on one side of the insulator, and into this a wooden peg is driven, which, passing downwards through the groove, locks the insulator fast. More recently glass studs, cemented into a porcelain insulator, have been adopted.

The conducting tubes are electrically connected by two wedges of drawn brass (not shown in the figure), which, when driven tight together, exactly fit the inside of the tube, the compound wedge being wrapped with wire to prevent it shifting. A little space is left between the ends of adjacent sections of the tubes to allow for expansion and contraction, which is, of course, considerable; in fact, the connecting wedges cannot be soldered to the tube as the expansion due to the difference in the temperature at night and noon would crack the solder. The two conductors, F F, form a single positive lead, and the collector places them in connection with one terminal of the motor, whose other terminal is connected to the wheels of the car, the return circuit being made through the rails, or, rather, through the earth. The two tubes are electrically connected at every hundred yards by a loop of insulated and lead-sheathed copper wire, placed in a groove cut in the sides and bottom of the channel. The resistance of the positive lead must be taken as that of the two tubes in parallel, and if the rails make good earth there will be practically no resistance between the negative terminal of the motor and the generator. But this would rarely or never happen, and to avoid any resistance at the junctions, adjacent rails are electrically connected by a strip of copper, the ends of which are plugged into holes punched in the rails.

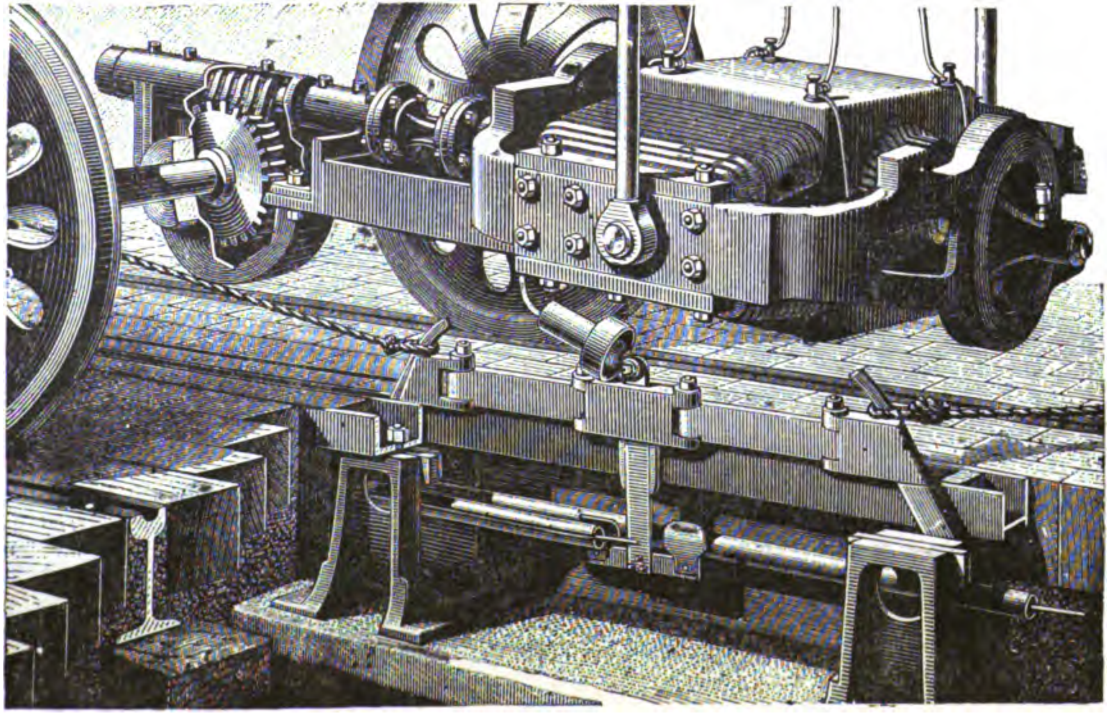
The engines and two generating dynamos are placed at the centre of the line. The generators are four-pole machines, each being separately excited by a small machine: a set of resistances is placed in circuit with the exciter and field-magnet coils, by varying which the strength of the field, and therefore, also, the E.M.F. developed by the generators, can be altered at will. The maximum E.M.F. of each is 300 volts, and the current 180 amperes. The two machines can, if required, be run together in parallel.

The maximum potential difference, viz. that at the centre of the line, is about 220 volts, and this falls gradually towards the two extremities. The deposit of moisture previously referred to is sometimes so great as to cause a serious leakage after the line has been standing idle during the night; in the earlier days this leakage has been known to reach 100 amperes, but the passage of the heavy current rapidly increases the insulation. Such improvements have since been effected that now the loss during working hours does not, under ordinary circumstances, exceed 3 amperes.

A good idea of the salient features of the system may be gathered from fig. 226. The collector, which is designed to run equally well in either direction, consists of two slanting clearing ploughs of tempered steel, connected by hinged wrought-iron plates to a centre-piece. This centre-piece consists of a cast-iron cheek, bearing on the edges of the steel troughing, and having fixed vertically through it a strong brass strip, which is well insulated and protected by hardened steel guards where it passes through the slot. The bottom of the strip is bare, and has fixed to it a short horizontal brass arm; which carries at each end two curved hard metal wings, facing in opposite directions, and each partly embracing one of the conductors. The whole forms a combination which is flexible enough to turn sharp bends, such as those at crossing points, is capable of clearing the opening of any slight obstruction, and ensures good electrical contact with the conductors. Each of the steel ploughs terminates in a finger, on to which is hooked a hauling rope, attached to the body of the car, but a loop of weaker cord is inserted, so that if the collector meets with a serious obstruction this loop breaks, the car passes on, and can be quickly brought to a standstill by the ordinary brakes. The loop slips off the trailing finger, and a detachable electrical connection is also provided, consisting of a clip, bored to receive a heart-shaped terminal, which can easily be inserted, but requires a rather sharp jerk to release it.

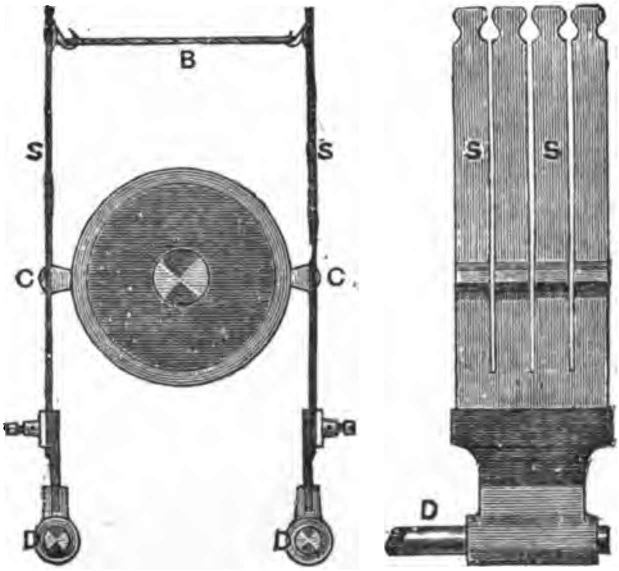
Mr. Smith has invented a great number of excellent devices in

FIG. 226.



connection with motors, motor regulation and gearing. He prefers, in most cases, to work with series motors supplied at an approximately constant potential, and those employed on the Blackpool line have proved very successful. Good wrought-iron is employed, but no practical advantages have been sacrificed for the sake of obtaining an extremely light and electrically efficient motor. The field-magnets develop a very powerful field, and the space between the iron of the armature core and the pole-faces is very small, the armature conductor consisting of one layer of silk-covered wire; consequently a comparatively weak armature field can be employed, and the distortion is practically nothing. In fact, the brushes can be allowed to make contact at the same place for either direction of rotation, without any appreciable sparking. This admits of the employment of an extremely simple and effective type of brush, which was invented by Mr. Smith for the purpose of enabling the armature to be run in either direction without

FIG. 227.

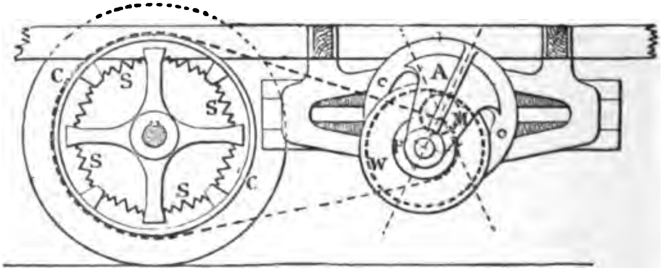


any alteration of the brushes, and to avoid the jolting of the car breaking contact.

Two views of these brushes are given in fig. 227. D D are the spindles passing through the holders to which electrical connection is made, S S being a thin flat steel spring, divided into four strips. The extremities of the springs are connected and drawn together by india-rubber bands B, and a small block of a special metal, C, is fixed to the middle of each strip, forming the contact with the commutator. This type of brush is, perhaps, the simplest and most effective that can be devised for the purpose; the wear takes place at the hard metal contact-pieces, which are so fixed that they can easily be taken out and replaced.

Fig. 226 illustrates the system as applied to a line in France, and an important feature is the worm-gearing. An endless screw gears with a wheel keyed on the axle, and the screw is connected to the armature spindle by a flexible joint, a certain amount of play longitudinally being also provided for. The screw and wheel are effectively protected by a casing, part of which is, in the figure, removed to show the interior. This gearing is now usually employed by Mr. Smith, but that devised by him for the Blackpool line is remarkably good, and is still in use there.

FIG. 228.



The latter arrangement is clearly shown by the diagram in fig. 228, for permission to reproduce which we are indebted to the Council of the Institution of Mechanical Engineers.

A side view of the motor is shown, and M is a pinion at the end of the armature shaft, gearing into an internal toothed wheel, W, that is, a wheel having teeth on its inner periphery. The pitch-circles of M and W are indicated by the dotted circles. On the outside of W, that is, on the side remote from the motor, is fixed a chain pinion, P, gearing by a chain with a chain-wheel, C, which is carried on the car-axle.

The chief objection to the use of chain gearing is that the chain always gets slack after a time, but a very simple and effective arrangement is introduced to take up the slack and so overcome this objection. The wheel W is carried by an adjustable bracket or arm, A, which is centred on the motor-shaft, that is to say, the arm is capable of being rotated about a centre which exactly coïncides with the centre of the shaft. Consequently, the pinion M and the wheel W remain in gear for every position of the arm, because the distance between their centres remains unaltered. The arm is locked in position by bolts passing through slots, and it is an easy matter to loosen these, rotate the arm through a small angle, and fix it in the new position if the chain becomes slack. The placing of a new chain in position also becomes a very easy matter.

A special device is also introduced to avoid a jerk at starting, which, as has been remarked, throws a severe strain on the gearing. The connection between the chain-wheel and the axle is not rigid, but is made through several stout spiral springs which yield and take the jolt off the chain when great pressure is suddenly applied. The chain-wheel C C consists of a loose annular rim, having four inwardly projecting pieces placed midway between the arms radiating from the hub which is keyed on to the axle. The ends of the arms are connected to the wheel C by spiral springs S S, as shown in the figure, and these springs extending allow the pressure to be applied more gradually.

The motors are series-wound, and supplied at an approximately constant potential, and the speed is regulated by the alteration of resistance joined in series with the motor; for, supposing the load to be constant, any increase of resistance reduces the current flowing through the armature and field-magnet coils, and so reduces the speed of rotation; while a reduction of resistance allows the current to increase, and therefore also the speed. The same resistances can also be used to regulate the strength of the current required in starting. The aim has been to make the arrangement thoroughly practical and workable without risk of error or damage by an inexperienced driver, and also to allow the variation of resistance to be made gradually, without employing a large number of coils. It is also necessary to provide a large surface for radiation in the case of the lowest resistances, because they have to carry a heavy current, and the heat generated is considerable. All these points are effectually provided for without introducing any complication whatever. The switch is in the form of a wooden cylinder with brass strips of various lengths on its circumference, which make reliable rubbing contact with stout flat springs, when the cylinder is rotated by an ordinary lever. Only four coils of about 1 ohm resistance each are employed; and by moving the switch lever the following nine changes can be made in the motor circuit, either rapidly, or slowly, step by step, as desired. The coils are denoted by A, B, C, D.

1. Circuit disconnected.
2. A, B, C, D in series.
3. A, B, C "
4. A, B "
5. A
6. A, B in parallel.
7. A, B, C "
8. A, B, C, D "
9. Resistance coils short-circuited.

It will thus be seen that not only are the lower resistances obtained without employing extra coils, but when the heaviest current is passing the heat generated is being spent upon the whole of the mass of the metal employed.

It is very significant that probably the best practical work in connection with electrical traction should have been accomplished by a man who is primarily a mechanical engineer. His success is chiefly due to the practical nature of his work, everything being designed to suit the conditions under which it is intended to be employed, and the capacity of the people who are to make use of it. He has also devised an 'overhead system, in which the current is led to the motor by a flexible conductor, attached to a collector which slides over two parallel overhead conductors. Such a system is less expensive in construction and easier of renewal or repair than an underground one, but is less safe, and is likely to have only a limited use on public roads in England.

Mr. Smith has lately designed another method of constructing an underground conduit. This is in principle similar to that already described, but is expressly arranged to admit of the construction and repairs being more readily, and therefore more cheaply, executed, and also to reduce the loss by leakage. The leakage at an insulator takes place over the surface, and the resistance offered by the insulator is proportional to the length of its surface in the direction of the flow, and inversely proportional to the width of the surface. By doubling the number of insulators, the width of surface, and therefore the leakage, is doubled, so that the number of points of support for the conductor should be as few as practicable. It will be remembered that at Blackpool the insulators are only about a yard apart; in the newer system this distance is extended to about 5 yards, but then it is hardly possible to employ a rigid conductor. Steel troughing, similar to that shown in fig. 225, is used, and the cylindrical porcelain insulators are placed vertically, carrying on the underside an iron hook which supports a short loop attached to a cable. The upper side of the insulator is of rather larger circumference than the lower, and the shoulder thus formed bears upon the periphery of a hole in a stout piece of wood, placed in the bottom of the trough. This piece of wood is split longitudinally, and the two parts are pressed together (so as to hold the insulator firmly) by a wooden wedge, which is driven between the side of the trough and the wood. Over the insulator the trough is covered with an easily removable iron plate, so that any renewal can be made without difficulty. The troughing is secured to the chairs by bolts passing horizontally through a hole in the side of the trough and a vertical slot in the chair, so that by merely loosening the nut of the bolts, the trough can be lifted out, and the channel laid quite open.

A stranded copper cable is selected for the conductor, and as the distance between the points of support is considerable, the sag on this heavy cable is also fairly great. The insulators supporting the two parallel cables are not placed opposite each other, but alternately, so that the highest point of one cable is opposite the lowest point of the other. The collectors are semicircular strips, carried one at each end of a flat spring, the strips running underneath and partly embracing the cables. The flat spring presses upwards sufficiently to allow the strips to just make contact with the cables at their highest points, and as the sagging parts of the cables are lifted up by the contact strips as they pass along a good rubbing contact is secured. For long lines one or two independent and carefully insulated main cables are also employed, these being connected to the bare conductors at various points by simple switches. The switches are easily accessible, and the bare conductors are divided into lengths terminating at the switches, so that any faulty length can be cut out until repaired.

A serious disadvantage attending the running of motors in parallel circuit, supplied with current at a constant potential, results from the fact that the current carried by the main leading wires is the sum of the current supplied to the whole of the motors. When the number is great, this main current becomes enormous, and the main conductors must be correspondingly massive, to avoid serious loss of power; and, of course, the greatest loss occurs at the time when it can least be permitted, viz. when the motors are demanding the maximum current. Many difficulties disappear in a system of distribution of power to motors which require to be supplied with a constant current, for all the machines can be joined in series, and the mains need only be of sufficient size to carry the current required by one machine instead of the whole of them. But other difficulties arise, chiefly in regard to the supplying of the current to the motors, sufficiently great, in fact, to make the parallel system on the whole more practicable. The series system has, however, recently received a promising development on a tram-car line at Northfleet, and we will briefly describe the leading features in connection with this undertaking.

A section through the track is shown in fig. 229. Between two rails, the outer one of which forms the tread for the car-wheel, is an opening, $\frac{7}{8}$ inch wide, to a conduit of the shape and dimensions indicated; the current is led from the generating dynamo to conductors placed in this conduit, and thence to the motors by suitable connections depending from the car, and passing through the narrow opening between the rails. At intervals of about 4 feet are placed cast-iron yokes or chairs, to the tops of which the two rails are bolted, the walls of the conduit between these yokes being formed of Portland concrete cement. An earthenware tube, 3 in. in diameter, is embedded in the concrete, as shown at A, and in this are placed cables forming the main conductors, the cables employed being insulated with ozokerised rubber, and having an insulation resistance of 7,500 megohms per mile. One cable, marked 'line' in fig. 230, is unbroken for the whole length of the road, while the other is divided into lengths of about 21 ft. The rails also are 21 ft in length, and on both sides of the joint are placed yokes, 1 ft. 5 in. apart, a chamber being formed in the space between them. In each of these conduit chambers is placed an arrangement known as the 'spring-jack' (illustrated in fig. 231), consisting of a pair of glazed earthenware blocks, supported by brackets, cast on to the joint yokes, the blocks facing

FIG. 229.

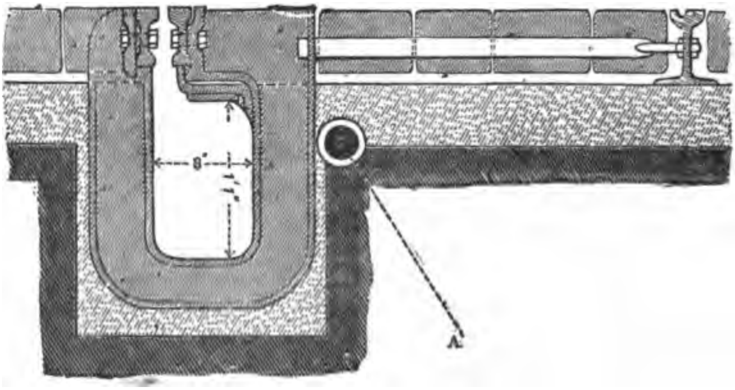
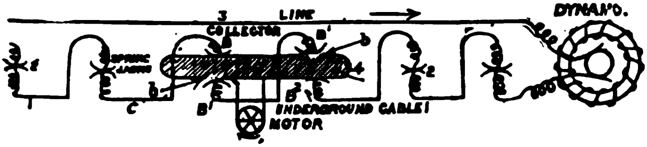
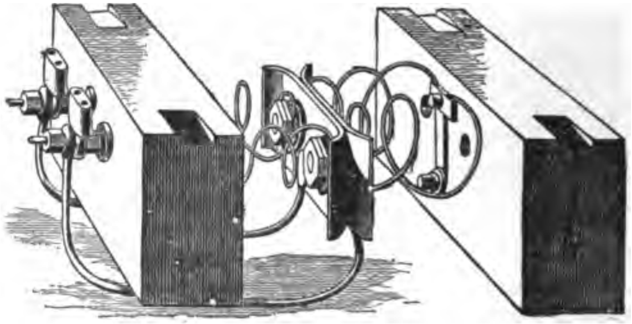


FIG. 230.



each other on opposite sides of the tube. To each block is attached, by means of a double-spiral spring, a gun-metal casting, curved at the ends, but flat in the centre, the springs being of sufficient strength to press the two castings together with a force of 6 lb. Two terminals are fixed on the outside of the left-hand block, each being electrically connected to one of the gun-metal strips as shown. The ends of that cable which is divided into 21 ft. lengths are connected to these terminals, so that throughout the whole of the line the gun-metal strips are in series with, and form part of, the circuit of the divided cable (see fig. 230). The current passes from one strip to the other, then by a length of cable to the next spring-jack, and so on; it is led to the motor by forcing two conductors between the strips, these conductors being insulated from each other and joined each to one of the motor terminals.

FIG. 231.



This collector, or 'arrow; as it is termed, is suspended under the car, and extends for its full length. It consists of two thicknesses of india-rubber belting, each having a broad brass strip riveted to it for nearly its entire length, and the nose at each end is shod with wrought-iron brought to a knife-edge, so as to easily force its way in between the two faces of the spring-jack. The maximum thickness of the arrow is 1 in., which is consequently the extent to which the gun-metal cheeks are separated. The conductor on each side of the arrow is lapped round one end, and an insulated space is left, slightly greater than the surface of contact of the spring-jack, near the extreme ends on opposite sides, as will be seen by the diagram in fig. 230, where *a* is the arrow, and *b b* the insulated spaces. In the position there indicated, the current passes from one contact strip of the spring-jack B^2, through the motor, to the opposite strip of the next spring-jack D, the strips D^1 B^1, together with the connecting length of cable between them, being cut out of circuit.

A moment later the collector will have left the spring-jack B^1 D^2, and the contact strips will fly together and complete the circuit, while the current will pass from the other strip B^1 through the motor to D, so that the current is never cut off, nor is the motor short-circuited.

The contact surfaces of the spring-jacks are placed in the middle of the conduit, and the collector arm is bent round, so that the collector also travels along the middle of the conduit; consequently the contact surfaces, not being directly under the slot, are fairly well protected from dirt or water entering from the roadway. Suitable outlets are provided for the escape of water and for the removal of any sand, stones, &c., which may accumulate, this latter operation being made easier by the fact that the conduit is empty except at the spring-jack chambers. The constant rubbing of the surfaces of the opposing gun-metal strips keeps them bright and ensures good contact when they are pressed together by the springs.

The motors are supported at one end by two bearings on the axle, and suspended at the other end by a spiral spring attached to a stout beam across the frame of the car. The speed of the motors is unusually low, viz. 400 revolutions per minute, the object being to avoid the use of a countershaft.

Worm-gearing is employed, reducing the speed in the proportion of 9 to 2; a double helical pinion on the armature shaft gears with a worm-wheel keyed on the axle, so that this wheel advances one tooth for every two complete revolutions of the armature.

The machines are series wound, and the regulation is controlled by two massive switches placed on the driving platform. In order to reverse the direction of rotation, the connections of the field-magnet are reversed by means of one switch; while the other varies the value of a set of resistance coils, which are joined up as a shunt to the field-magnet coils, and afford a means of weakening or strengthening the field according to the power and speed required.

The current through the armature being kept constant, the maximum power is obtained when the field-magnets are unshunted and take the whole of the current, and this arrangement would be adopted for mounting an incline, while, if less power is desired, the field can be weakened by shunting the field-magnets. The shunts are arranged to provide for three speeds, and, in order to stop the car, the field-magnet is short-circuited, the current still passing through the armature.

In starting a motor worked on the parallel system, there is sometimes a risk of the armature being damaged by the passage of a heavy current; for there is a constant potential difference maintained at the terminals sufficient to determine a dangerous current, should the armature fail to quickly get up speed and develop an opposing electro-motive force. No such danger exists in the series system, the current strength being constant under all conditions.

In the case under notice a Statter constant-current dynamo is employed for the purpose of generating the current. The method by which the regulation of this machine is effected has already been fully described.

The pressure at the terminals varies from a small value up to nearly 500 volts, according to the demand made by the motors; and a considerable difference is made in the power expended by reversing the field-magnet connections on the car, when it is running down-hill and when no power is required. The effect of this is to turn the machine into a generator for the time being, its E.M.F. *assisting* that of the main generator and reducing the demand made upon the latter; so that a large amount of the energy stored in the car during its journey up-hill may be usefully employed, instead of all being wasted as heat at the brakes; and when a large number of cars is employed on an undulating line, this becomes an important advantage. It should be observed that although a motor supplied at constant potential, in parallel circuit with others, may dam back the current when the speed rises in running down-hill, and so absorb less power, yet it cannot actually assist the source of supply in feeding the circuit, until the speed becomes sufficient for the machine to develop an E.M.F. higher than that maintained by the generator

An important operation in connection with a dynamo-machine is the determination of its commercial efficiency; that is, in the case of a generator, the ratio of the electrical power appearing in the external circuit and available for useful work, to the total mechanical power spent in driving the machine; and, in the case of a motor, the ratio of the useful mechanical power obtained on the armature shaft to the total electrical power absorbed. The accurate measurement of the mechanical power in either case presents some difficulty. The usual method is to employ a transmission dynamometer, or a friction brake, to determine the horse-power expended or obtained, as the case may be, but it is not possible with either class of apparatus to be certain of obtaining any but an approximately correct result. The electrical power, on the other hand, can be measured with extreme accuracy, it being simply necessary to find the current strength in, and the potential difference at the extremities of, the external circuit of a generator; and the current passing through a motor, together with the E.M.F. at its terminals; the product of the two quantities in either case, gives the power in watts.

If it were possible to arrange matters so that it would become essential to measure, by a mechanical process, only a small fraction of the total mechanical power given to a generator, say one-tenth (the other nine-tenths being measured electrically), then a much more accurate result might be obtained; for any error made in measuring this fraction, when distributed over the whole amount, would have but one-tenth the value of that which would otherwise accrue. And, further, it is far easier to accurately determine the value of a small, than of a fairly large amount of mechanical power.

An important departure, rendering such a method possible, was made some time since by Dr. Hopkinson. He takes two approximately equal machines, and, driving one as a generator, leads wires from it to the other, so connected that the current developed by the first machine drives the second as a motor.

Now, the power appearing on the motor shaft is less than that spent on the generator, by an amount equal to the power absorbed by friction, by the heating of the various conductors, armature cores, &c., in the two machines.

But the power which does appear on the motor-shaft might easily be employed to assist in driving the generator; and this is effected by the simple process of rigidly coupling the shafts of the two machines together; so that, then, the only mechanical power required to be supplied and measured, is an amount equal to that just referred to as being wasted in the various parts during the double conversion.

This fraction, thus supplied, is conveniently measured by a dynamometer of the Hefner-Alteneck type, which measures directly in pounds the difference between the pull on the tight and slack sides of the belt, that is, the actual pull causing the rotation of the pulley. This number, multiplied by the number of feet travelled by the belt per minute, gives the number of foot-pounds of work performed in one minute, which, divided by 33,000, gives us the horse-power supplied by the belt; since one horse-power is a rate of working equal to 33,000 foot-pounds per minute. With the particular dynamometer employed in one test made by Dr. Hopkinson, the pointer moved over one division of the scale for a pull of 2·705 lb. on the tight side of the belt in excess of that on the slack side, and the radius of the pulley was such that one revolution corresponded to an advance of the belt through 3·63 feet; in this case, then, the work done per revolution was $2{\cdot}705 \times 3{\cdot}63$ foot-pounds, for one scale-division.

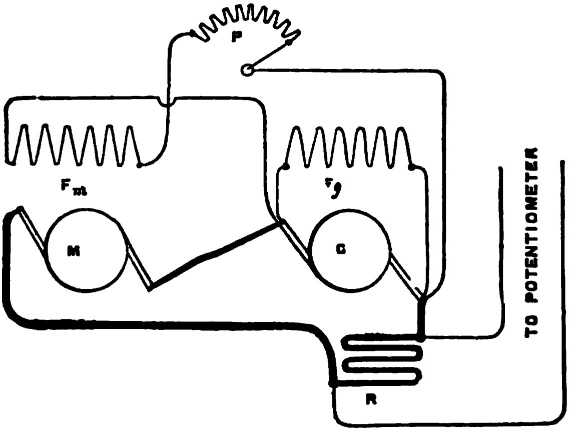
From this it will be seen that if T represents the number of scale divisions traversed by the pointer, and n the number of revolutions per minute, then the power applied $= \frac{2{\cdot}705 \times 3{\cdot}63}{33{,}000} \times n \times \mathrm{T} = 0{\cdot}000298 \times n \times \mathrm{T}$ horse-power.

A number of experiments were made with the machines in the case under notice, and, as they are interesting, the full results of one test, as furnished by the experimenter, are appended.

The electrical connections were made as in fig. 232, where G and F g represent the armature and field-magnet of the generator, and M and F m those of the motor. The heavy lines indicate the main connections between the two machines, and, in order to measure the current, a small accurately known resistance, R, is placed in the main circuit; to the extremities of R, are connected wires leading from a potentiometer, by means of which, with a Clark standard cell, the potential difference between the ends of the resistance can be accurately measured.

This potential difference, divided by the resistance (which was in this case 0·0058 ohm), would give the current flowing through the main wire. The potential difference between the terminals of the generator was measured by a Thomson graded voltmeter, previously standardised by a Clark cell.

FIG. 232.



Now, the two machines were exactly alike, and, consequently, if joined in opposition (as two shunt machines must be, when one is required to drive the other), and then driven at equal speeds, no current would flow from one armature to the other, for they would generate equal E.M.F.'s, or, in other words, the counter-electro-motive force of the motor would be equal to the electro-motive force of the generator. For this reason, it is necessary to weaken the strength of the motor field, and this was effected by placing a set of variable resistances, P, in series with the motor field-magnet coils; and, by altering this resistance, the current passing through the motor armature could be varied at pleasure. The motor field-magnet coils, together with P, form a shunt to the generator terminals; the motor armature thus receiving the whole of the current passing through R. And, since the resistances of the two field-magnet circuits are known, the current in each can readily be calculated after the potential difference at the generator terminals has been measured.

The resistances of the armatures and field-magnet coils of the two machines were :—

Generator . .	Armature . .	0·009947 ohm.
	Field-magnets .	16·93 „
Motor . . .	Armature . .	0·009947 „
	Field-magnets .	16·44 „

1. The two dynamos were run with brushes removed and with the fields unexcited.

Scale reading = 21·6 divisions.
Revs. per minute = 808.
Horse-power = 5·2.

2. The two fields were separately excited, and the dynamos driven, still with the brushes off, when

Scale reading . . . = 30 divisions.
Revolutions . . . . = 802.
Shunt current in field of generator = 6·9 amperes.
„ „ „ motor . = 6·7 „
Horse-power . . . . = 7·169.

3. The connections were made as in fig. 232, and the following results were obtained :—

E.M.F. at terminals of generator . = 110·12 volts.
Main current . . . . = 358 amperes.
Current through generator magnets = 6·50 „
Current through motor magnets . = 5·36 „
E.M.F. at terminals of motor . . = 107·33 volts.
Speed of machines . . . = 764 revs. per minute.
Power transmitted by belt . . = 6602 watts = 8·850 h.-p.

Hence—

Total power given to generator . = 42917 watts = 57·53 h.-p.
Power lost in armature core . . = 831 „ = 1·11 „
Power lost in generator magnets . = 716 „ = 0·96 „
Power lost in generator armature . = 1360 „ = 1·823 „

And therefore—

Commercial efficiency . . . . = 93·23 per cent.
Loss in core . . . . . . = 1·94 „
„ magnets . . . . = 1·66 „
„ armature . . . . = 3·17 „

Similarly for the motor—

Total power given to motor . = 38886 watts = 52·13 h.-p.
Power lost in internal friction of core . . . . . = 831 „ = 1·11 „
Power lost in motor magnets . = 472 „ = 0·63 „
„ „ „ armature . = 1275 „ = 1·70 „

And therefore—

Commercial efficiency of motor . . = 93·37 per cent.
Loss in core . . . . . = 2·14 „
„ magnets . . . . = 1·22 „
„ armature . . . . = 3·27 „

The loss due to friction of the bearings and one or two unimportant causes, has then to be determined and deducted, to obtain the real commercial efficiency, which, after this deduction, was found to be: motor 92·6 per cent., and generator 92·5 per cent.

These efficiencies are phenomenal, and would seem to indicate some error in measurement; but the method itself, being a good one, merits careful attention on the part of the student.

One disadvantage of the original method is that it is necessary to have two approximately similar machines in order to perform the test, and this is sometimes inconvenient. A number of modifications of the method have, however, been suggested, the measurement of even a fraction of the power mechanically being in some cases avoided by obtaining the extra power representing the total waste by means of a small motor, and measuring the amount so supplied, electrically.

Any one of the alternate-current dynamos described in Chapter VIII. can be used as a motor; that is to say, its moving parts can be caused to rotate, and mechanical power obtained on the armature or field-magnet shaft, as the case may be, by supplying power electrically by means of a suitable *alternating* current. Such machines have some important advantages, and some serious disadvantages; there is no doubt, however, that the latter will shortly be overcome, as at the present moment more energy is being brought to bear upon the evolution of a practical alternating current motor, than upon any other electrical problem.

The chief advantages are, first, that the electrical power can better be supplied at a high potential difference with a comparatively small current, thus minimising the loss in the conducting leads; and, secondly, that the machine is perfectly self-regulating as regards speed, in spite of load variations, for it keeps perfect time with the generator. Its speed can readily be varied by varying the rate of alternation of the supply current, although this method is impracticable for obtaining frequent speed alterations, or if the same generator is supplying more than one motor. The necessity for an alternating motor is apparent, since so much distribution for lighting purposes is now being effected by alternating currents, while up to the present no satisfactory motor is available for general use on such a circuit.

The principal disadvantages are that the machine cannot start itself, as can a direct-current motor, but has to be independently driven up to the speed of the generator; while if the load is made excessive the motor stops entirely, and has to be again started by some external means. The machine will, however, make great efforts to respond to the extra work thrown upon it, and to keep in synchronism with the generator, but will surely fail immediately the load is sufficient to drag it out of unison.

It is extremely inconvenient, and requires considerable power to start a large machine, whence any device to facilitate this is very welcome. Perhaps the most practical method yet devised is that due to Mr. Mordey, who employs for the purpose the small machine used to excite the field-magnets. This, as seen in fig. 140, is coupled direct to the main-shaft, and its current at times passes through and charges a small secondary battery. When the machine is to be started the current from the battery is passed through the exciter for a minute or two, converting it into a motor, which puts the alternate-current machine into rotation. As soon as synchronism between the motor and the generator is obtained, the former is switched into circuit and continues to run.

Some extremely good results have been obtained with Mordey alternators when used as motors, proving them to be all that can be desired for classes of work in which the speed does not require to be varied, or where frequent stoppages are not necessary.

From these motor properties of an alternator, results the very important fact that two independently driven alternating generators can be run in parallel, that is to say, their armatures can be connected in parallel so that the two machines can jointly supply power to the external circuit. It is, however, essential that the two machines shall give the same rate of alternation, and also run co-phasally, that is to say, the maximum positive electro-motive force, and also the maximum negative electro-motive force of the two machines must coincide in point of time. Then the resultant E.M.F. is the same as that of one, while the current, and also the power developed, will be doubled. Now the remarkable fact is, that the two machines will make great efforts to keep in phase, and will do so, even if the mechanical power supplied to one is increased or diminished within a reasonable limit. To explain this extremely important mutual action we may remember that the reaction between the armature and field magnets of a direct-current dynamo is such as to tend to stop the rotation, and this tendency becomes stronger as the current in the armature increases, while a weakening of the current of course reduces the resistance to rotation. The speed might therefore be diminished by increasing the current flowing through the armature, by some external means, while by inserting an opposing E.M.F. in circuit, and reducing the current, the speed could be increased. And if the opposing E.M.F. exceeded that developed by the machine, the current through the armature would be reversed, and the machine would run as a motor.

Now, these effects can be obtained with an alternate-current dynamo. That is to say, if the brief currents generated by it are increased in strength, the tendency will be for the machine to slow down, while if an opposing alternating E M.F. acts in such a manner as to reduce these currents, the machine will quicken its speed, and it will run as a motor, doing work for the moment on the prime mover, if the opposing E.M.F. is sufficient to determine a current in the reverse direction.

Now when two alternators are driven independently and coupled in parallel, and one begins to lag behind the other, the maximum E.M.F. of the leading machine occurs a moment earlier than that of the other, and consequently a heavy current flows from the leading to the lagging machine for a very brief interval of time This current being opposite in direction to that which is then being generated by the lagging machine, tends to drive it as a motor and to accelerate its speed; or if the difference of E.M.F. is not sufficient to set up a reverse current, it weakens the existing one with the effect of allowing the lagging machine to catch up, as already explained. On the other hand, the later occurring E.M.F. of the lagging machine will tend to increase the current in the leading one and so pull it up. These reactions will commence immediately the alternators tend to get out of phase, and in well-designed machines the effect is so prompt and forcible that they run together perfectly in spite of inequalities in the driving. It becomes very important, therefore, to decide what qualities and peculiarities a machine should possess to fit it for parallel working. Until recently it had been supposed that it was absolutely necessary for such a machine to have considerable self-induction, but even then the performance was admitted to be somewhat difficult and uncertain. Consequently, an armature without an iron core, and with few convolutions, was deemed to be undesirable; but these views have been somewhat shaken, and, to a great extent, entirely reversed, by the recent researches of Mr. Mordey. That gentleman starts with the assumption that since the maintenance of synchronism depends upon the motor properties of the two alternators, the machine best fitted for parallel working must be one which possesses these properties to a high degree.

Consequently, the armature should have little resistance, and very little self-induction, and then the transfer of power by means of brief currents from one machine to the other, which serves to hasten or retard as required, takes place much more suddenly, and the regulating action is much more prompt and forcible. Of course, the armature will have some self-induction and some resistance, but it is satisfactory to know that neither of these undesirable factors need be made abnormally high, merely for the sake of rendering parallel working practicable. It is probable, however, that there is a limit depending upon other conditions, (such as the rate of alternation,) below which it is inadvisable to reduce the self-induction, and that some definite relationship between self-induction and resistance should exist for any given case ; but, on the other hand, it is possible that this limit is very low, and that the working rule will be to make the two factors concerned as low as is practicable.

In the Mordey alternator, which has no iron in the armature, self-induction has a low value, so low, in fact, as to unfit the machine for parallel working if the old theory were correct. In order to support his views on the subject, the inventor made an exhaustive series of tests with two of these machines, each being similar in appearance to that depicted in fig. 140, but having an output of 50 horse-power, with a maximum E.M.F. of 2,000 volts, at a speed of 120 revolutions per minute. The details of one set of tests are given below. It should be noted that the machines were driven by two independent engines, not connected in any way, and provided with heavy fly-wheels ; each engine also drove a heavy set of countershafts, fitted with a number of belts, &c., so that the momentum was considerable.

1. The alternators were run up to full speed, and each excited to give 2,000 volts. When in phase they were switched in parallel without any external load, and without the insertion of any self-induction coils or resistance between them. They ran in parallel perfectly.

2. A considerable inductionless load was then put on, varied, and taken off. They ran equally well under all circumstances.

3. They were uncoupled, and then, the load being connected to the mains, they were suddenly and simultaneously switched in parallel and on to the mains with perfect success.

4. One alternator was excited to give 1,000 volts, the other giving 2,000 volts. They were then switched in parallel, and went into step perfectly, giving a terminal potential difference of about 1,500 volts. No extra self-induction or resistance was inserted in this or in any other case. A load was then put on without affecting their behaviour.

5. With one machine at 1,000 volts and the other at 2,000 volts, they were switched in parallel when out of phase, and instantly went into step. A large current appeared to pass between them for a fraction of a second, but not nearly long enough to enable it to be measured or to do any harm.

6. They were then left running in parallel while one was disconnected from the engine, by its belt being shifted from the fast to a loose pulley. It continued to run as a motor synchronously. A load of lamps was at the same time on the circuit.

7. The two machines were then uncoupled and excited up to 2,000 volts. They were then switched in parallel when out of phase and without any external load, and went into step instantly.

8. Whilst running as in 7, steam was suddenly and entirely shut off one engine. The alternators kept in step perfectly, one acting as a motor and driving the large engine and all the heavy countershafting and belts. It was impossible to tell, except by the top of the belt becoming tight instead of the bottom, which machine was the motor.

To find the power exerted by the alternator acting as a motor in 8, a direct current motor was put in its place, and the power required to drive the engine and shafting was found to be 20 horse-power.

The above results speak for themselves; but a word of explanation may be given with respect to No. 5. There is an E.M.F. in excess, of 500 volts, which would be competent to send an enormous current through the low resistance of the two armatures, the low self-induction not being able to prevent it, even though it is only applied in the same direction for a very brief moment. No such dangerous current was observed, and there must evidently be some other cause to prevent or modify it. This rather interesting point has been very simply explained by Sir William Thomson, who points out that the effect of a sudden increase of the current at any instant through the two armatures, in the direction determined by the excess of E.M.F. of the more powerful machine, is to tend to increase the strength of the field of the weaker, and to decrease that of the stronger machine. So that although a strong current would be started round the two armatures, its effect would be to immediately strengthen the field of the 1,000-volt and oppose that of the 2000-volt machine, until the E.M.F. developed by each would have nearly the same value, viz. 1,500 volts. This brief equalising current would pass twice for every complete alternation.

CHAPTER XIII.

TRANSFORMERS.

WHEN it is desired to convey energy to a distance by means of electricity, either for the purpose of producing light or mechanical motion, the chief problem to be faced is, how to reduce to a minimum the waste of energy during the transmission. We have seen that when a wire is used to convey a current, the rate at which energy is lost in that wire can be measured by multiplying together the current strength in amperes and the difference of potential between the ends of the wire in volts, the result being the number of watts so expended. And since the electro-motive force is equal to the product of the resistance of the wire and the current flowing, the loss in watts may also be calculated as the product of the resistance and the *square* of the current strength. That is to say, in the first place the power expended in any part of a circuit is proportional to the resistance of that part. Suppose, for example, a dynamo were employed to furnish current to a number of lamps arranged in parallel, their joint resistance being 10 ohms; then if the resistance of the machine and leads or connecting wires were also 10 ohms, exactly as much power would be wasted, as would be usefully expended in the lamps, a state of affairs which manifestly could not be tolerated. If the resistance of the machine and leads were reduced to 1 ohm, then the power wasted would be one-tenth of that usefully employed, and so on.

The resistance of the combination to which power has to be supplied is, as a rule, extremely low; and when the lamps or motors are joined in parallel, the current carried by the mains is equal to the sum of that required by the whole of them. Consequently the resistance of these mains must be kept extremely low, a small fraction of an ohm in fact, otherwise the proportion which the power wasted bears to the total quantity of power developed becomes excessive. To keep the resistance low copper of high conductivity must always be employed, but the practical limit as regards sectional area is quickly reached on account of the high price of that metal.

Speaking generally, it may be said that transmission of energy to any distance by electricity is not economical, if we depend upon reducing waste merely by increasing the conductivity of the leads. Again stating the case as:

$$\text{Watts lost} = C^2R,$$

where R is the combined resistance of the leads and generator, we see that the only other way out of the difficulty is to reduce the current strength.

If this can be done the advantage is very decided, for, by halving the current, the power wasted in any portion of the circuit is reduced to one-fourth. It may not, however, be evident at first sight, how with this reduced current the same amount of energy can be transmitted in an equal time.

Digressing for a moment, in order to introduce an analogy, the student will probably be aware that in transmitting power mechanically to a distance by a slowly moving cable, it is imperative that the cable and the rest of the moving parts shall be very strong and massive, and consequently the power lost by friction, &c., becomes enormous. But the energy transmitted per minute is equal to the pull on the cable in pounds, multiplied by the distance in feet through which the cable moves in a minute; so that, by increasing the velocity of the cable, the strength and size of it and of the other moving parts can be correspondingly reduced without reducing the amount of energy transmitted per minute. It is in fact possible to transmit enormous power by means of a light wire cable, if it travels with sufficient rapidity; and the loss due to friction is obviously reduced with the reduction in size and weight of the moving parts. Even if it is essential for the power so transmitted, to be taken, say, from a slowly rotating wheel, it is still economical to transmit it at a high velocity, and effect the necessary reduction in speed by suitable gearing.

Somewhat similarly, very great power can be conveyed electrically by a comparatively small current traversing a thin wire, if only the electric pressure or potential difference is sufficiently high; for the power in watts may be calculated as the product of these two factors, and no difference in the amount is made by reducing one of them, if the other is increased in like proportion.

But unfortunately it rarely happens that electrical power can be utilised at a high pressure; for instance, 110 volts is usually the maximum pressure required by a set of incandescent lamps joined up in parallel, and consequently it becomes necessary to employ, if possible, some arrangement which shall perform the same function as does mechanical gearing in reducing speed. That is to say, we require some apparatus competent to receive electrical power in the form of a small current at a high potential difference, and again give out that power in the form of a heavy current, and at a correspondingly lower potential difference.

It is possible to construct such apparatus; and before proceeding further we may notice the two chief points to be borne in mind in designing it:—

1. The proportions of the parts must be so calculated that the reduction is effected in the desired ratio; or, the value of the resulting potential difference must be the required fraction of that applied to the apparatus.

2. The loss in power during the conversion must be kept as low as practicable; that is to say, the design must be such that the efficiency of the apparatus is high.

The conversion from a high to a lower potential is rendered possible by the fact already fully explained, that by starting or stopping a current in a circuit, a brief current can be induced in a neighbouring wire. The circuit in which the original current is started or stopped is called the 'primary' circuit, while that in which the currents are induced is called the 'secondary' circuit.

In order to obtain the maximum effect, it is necessary to arrange that the secondary circuit is cut by as many as possible of the lines of force generated by the primary. The best method is to wind the wire in two coils, and placing them close together, provide plenty of iron in the vicinity in order to make the primary lines of force extend out beyond the secondary coil. The iron should in fact form a closed magnetic circuit of low resistance, embracing both coils. But since the rapid reversals of the current generate eddies, the iron must be carefully laminated; in any case, a certain amount of power is wasted by hysteresis.

Suppose the number of convolutions in the two coils to be equal; then by sending a rapidly alternating current through the primary, an alternating current of about the same strength might be obtained in the secondary. Again, the secondary might consist of a great length of wire in many convolutions, thin wire being employed to enable it to be kept near to the primary. In this case the primary lines of force would cut the secondary circuit many times, and the induced E.M.F. would be much greater than that urging the current through the primary. But since the power obtained from the apparatus cannot be greater than or even equal to that given to it, a corresponding reduction in the other factor would be observed; in other words, while the E.M.F. had been enormously increased, the current would have been far feebler than that in the primary.

The student is probably familiar with a piece of apparatus known as an 'induction coil,' in which a rapidly interrupted heavy current of low E.M.F. is passed through a few turns of wire, adjacent to an enormous number of turns of finer wire. A bundle of thin varnished iron wires serves as a core, and a very feeble current of extremely high E.M.F. can be obtained in the secondary circuit. Such apparatus has proved of extreme value in experimental researches; but it can hardly be said to have any very great importance from a commercial point of view.

We are far more concerned with the effects obtained by proceeding in the reverse order, viz. by making the length of the primary much greater than that of the secondary.

Supposing, for instance, we use the fine wire coil of an ordinary induction coil as the primary, and the thick wire coil as the secondary; the former offers considerable resistance, and it will require a high E.M.F. to send an alternating current of even feeble strength through it. But on measuring the resulting current in the thick wire coil (now being used as the secondary), it will be found that while the E.M.F. is low, the current passing through this low resistance circuit is comparatively very heavy. It is a most important fact that by constructing such an induction coil so that nearly all the primary lines of force can effectively cut the secondary, the secondary E.M.F. can be made to bear nearly the same ratio to the primary E.M.F. that the number of convolutions in the one coil bears to the number in the other. Therefore, by making the resistance of the magnetic circuit, and the electrical resistance of the secondary circuit, both very low indeed, we can obtain at the terminals of the latter, an alternating potential difference whose average value is almost equal to a definite fraction of the average of the alternating potential difference maintained at the primary terminals.

For instance, if the primary consists of 1,000 turns and the secondary of 10, and a current of 1 ampere passes through the primary coil while the potential difference is 500 volts, then the secondary current may be 100 amperes, and the induced E.M.F. rather less than 5 volts. This is the important case with which we have to deal, for it thus becomes possible to effect the much-desired object of transmitting electrical power at a high electrical pressure. and employing it at the required point at a lower pressure. A piece of apparatus which is capable of effecting this transformation from high to low E.M.F., is called a 'transformer.'

The first transformer was constructed in 1831 by the immortal Faraday. The principles which he then discovered, of the remarkable action of a varying current upon an adjacent circuit, are of almost inconceivable importance; while the method of constructing his original transformer, which we shall briefly describe, was well abreast of the then existing practice.

Faraday procured a welded ring of soft round bar iron, $\frac{7}{8}$ inch thick, the external diameter of the ring being 6 inches. Round one part of this ring he wound about 72 feet of copper wire. $\frac{1}{20}$ inch in diameter, in three superposed helices, the distance round the ring thus covered being about 9 inches. The wire was bare, the first helix being insulated from the iron by a layer of calico, and twine was wound side by side with the wire, to prevent contact between adjacent convolutions. Then followed another layer of calico, over which was wound the second helix, insulated with twine similarly to the first, then another layer of calico followed by the third helix, the whole being covered by calico.

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